# STRAY CURRENTS

FROM

# ELECTRIC RAILWAYS

MICHALKE

# AUTHOR'S PREFACE

MUCH has been written in the different technical periodicals concerning leakage currents from electric railway returns, but it is often impossible to consult all these different papers, and in any case it is difficult to quickly obtain a general idea of the subject.

The railway engineer, who designs and constructs the system; the gas and water engineer, who lays the pipes; the chemist, who investigates the corrosion effects; the companies, who own the properties concerned; the physicist, the telephone and telegraph men, are all interested to know to what extent leakage currents are liable to create disturbance or do damage, and how such evils can be prevented. Since the various parties have different points of view concerning the subject, it seems that an impartial sifting and rearrangement of the material already on hand would possibly inspire new works and investigations, which would do much to clear up the matter. Thus, in accordance with Dr. Benischke's request, I have collected the material concerning stray currents and issued the same in one book of the series, "Elektrotechnik in Einzeldarstellungen." The contents of this book should not and could not give any general method of preventing the disturbances, since too many factors, which depend upon local conditions, enter in the problem. The book should, however, quickly supply information on any one of the different parts of the subject.

Since the means of preventing and controlling the danger rests upon the knowledge of the distribution and strength of the stray currents, the subject has in part been treated

mathematically. The formulas developed should simply show the relative influence of the different factors. All the calculations in the text are elementary in character, the rigorous mathematical treatments being given in the foot-notes.

DR. C. MICHALKE.

CHARLOTTENBURG, June, 1904.

## TRANSLATOR'S PREFACE

ELECTROLYSIS is a disease most largely peculiar to America, and therefore a book such as Dr. Michalke has produced is of prime interest to us.

The Europeans have experienced little trouble from the corrosive action of return currents, but the reports of the "horrible" cases in this country aroused their fears and they at once set to work to determine the state of affairs in their own countries.

Extensive investigations were undertaken on all sides and many valuable and thoroughly scientific reports were the outcome. It is from these reports printed in the various European periodicals that this book has been compiled.

The translator has added an extensive bibliography and a few foot-notes from American practice.

THE TRANSLATOR.

# CONTENTS

# SYMBOLS USED IN THE FORMULAS

$R$, $R_r$ = Resistance of rails per unit length.
$R_p$ = Resistance of pipes per unit length.
$r$ = Resistance of leakage paths per unit length of track.
$r_s$ = Surface resistance.
$r_e$ = Resistance of soil.
$L$ = Half the distance between feeding points.
$l$ = Distance measured from feeding point.
$x$ = Distance measured from middle point.
$d$ = Distance of the neutral point from middle point.
$\delta$ = Distance perpendicular to the rail.
$E$ = Potential.
$E_l$ = Potential drop in the length $l$.
$E_x$ = Potential drop in the length $x$.
$e$ = Potential of the rails or the pipes with reference to the earth.
$e_l$ $e_x$ = Potential of the rails or the pipes with reference to the earth at the distance $l$ or $x$ from the feeding point or middle point.
$I$ = Total power current.
$i$, $i_o$, $i_l$, $i_x$ = Leakag ecurrent, at the feeding point, at the distance $l$, and at the distance $x$.

### ABBREVIATIONS

V. D. E. Verband Deutscher Elektrotechniker.
E. T. Z. Elektrotechnische Zeitschrift.
D. R. P. Deutsches Reichspatent.

# STRAY CURRENTS

## CHAPTER I

### INTRODUCTION

By suitable insulation it is always possible to so protect a conductor of electricity that no perceptible leakage to the surrounding medium can take place, even though this medium be a good conductor.

However, if it is impossible to so insulate the conductor from the surrounding medium the latter will take part in carrying the current. This is the case when rails are used for the return circuit. A part of the current branches off into the earth, returning again to the rails at certain fixed points. These currents are called stray currents. These stray currents also occur, though to a lesser extent, in three-wire systems with a bare middle conductor, and many times to a greater extent in cables which have bad faults.

Faults in cables generally produce only local disturbances, which in most cases are easily located and quickly remedied.

The stray currents in a three-wire system with a bare middle wire may be kept so small, by balancing the loads in such a way as to give a proper current distribution, that no harm can result from them. For this reason in the following discussion the stray currents in electric railway systems will be particularly considered.

These stray currents work to reduce the load on the rails, because the conductivity of the return path is greater than that of the rail alone. Therefore, both the drop in poten-

tial and the $I^2R$ losses will be reduced. From this it follows that it would be advantageous to use the earth as part of the return circuit were there not several resulting evil effects.

Earth currents produce fluctuations in the value and direction of the earth's field.

Therefore, when these currents exist, measurements in which the earth's field plays a part are disturbed or rendered impossible. The constant changing in direction and intensity of these earth currents, due to the varying load on the system, makes it impossible to bring an unprotected galvanometer needle to rest.

Furthermore, telegraph, telephone, and signal systems which have a ground return are liable to very disagreeable disturbances, arising from the stray currents in electric railway systems.

While the above-mentioned disturbances may be accurately observed and controlled, there are certain electrolytic effects which take place beneath the surface of the earth, and these are exceedingly difficult to deal with. By electrolysis, metallic masses which are buried in the earth become corroded at those portions where the stray currents leave them to re-enter the soil.

From this it is seen that warning must be taken, because precisely at those places where the traffic is heaviest and the currents to be carried by the rails greatest, there are also located the most extensive networks of iron pipes. The prevention of the destruction of pipe lines by stray currents from electric railways is one of the most important problems in street railway engineering.

## CHAPTER II

### STRAY CURRENTS WITH A UNIFORM CURRENT LOAD ON THE RAILS

If the rails of an electric road are not insulated from the earth they will not carry the total current all the way to the power house (Fig. 1); a part will branch off into the soil and flow through the surrounding medium returning

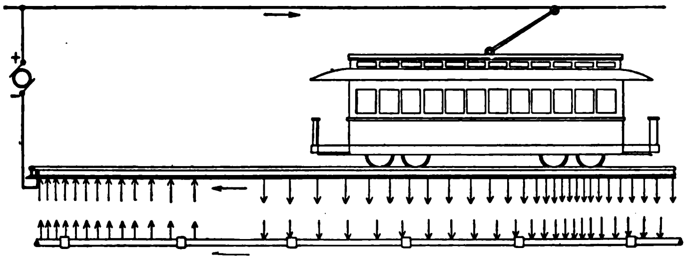


FIG. 1.

to the rails at certain fixed points. This branching off of current depends upon the conductivity of the earth and the position and character of metallic masses which are buried in the earth. Underground water, rivers, lakes, etc., influence more or less the path of earth currents. But extensive pipe systems which are connected so as to form good conductors have a still greater influence.

The currents which leave the rails to enter the earth have first a surface resistance $(r_s)$* to overcome, which may be thought of as a thin layer of poor conducting mate-

* Ulbricht, *E. T. Z.* 1902, p. 212.

rial. Then the resistance of the surrounding medium ($r_e$), which depends upon the character of the soil and masses of metal that are buried in the vicinity, must be overcome. Combining these two resistances $r_s + r_e = r$, we obtain the total resistance ($r$), and, in general, we may consider this quantity alone as the resistance offered the current in passing from the rails to the ground water or to nearby pipe lines. The calculated values of current based on this assumption are rather too great, but may be taken as limiting values. The greater the resistance $r_e$, or the potential difference between the rails and the earth, the greater the excess of the calculated values over the actual. Thus it is seen that the error would be greater for suburban roads than for street railways, where the potential difference is partially equalized through the pipe systems. In any case the error is not so great as to seriously affect the accuracy of the results.

When it is possible for the current to distribute itself through a considerable area of earth, the resistance depends largely upon the amount of surface which the metallic conductor presents to the surrounding medium. When current flows between two metallic balls* buried in the earth, the resistance depends less upon the distance between the balls than upon the area of their surfaces.

When, as is generally the case, the trolley wire is connected to the positive bus bar and a car is in a given section (Fig. 1), the currents leave the rails at the point where the power is used and return at the feeding points. On the other hand, where pipe lines have good electric joints, the currents enter at the points where the power is used and leave at the feeding points. In the middle of the section there is a place where no current flows in either direction. If the rails are connected to the negative bus bar, then

* Bell, "Power Distribution for Electric Railways," p. 35.

good conducting pipe lines are exposed to danger in the vicinity of the feeding point. *

By making certain assumptions, such as, that the rails are continuous without branches and the car is at the end of the section (as in Fig. 1), the approximate value of the stray current may be easily calculated.

Let Fig. 2 be a diagrammatic representation of the problem; $A$ is the feeding point, $AB$ the section of the length $L$, and $B$ the point where the power is used. Let the total current used by the car be $I$, and in the earth (water or complex pipe system) let there be no potential differences worth mentioning. Then the distribution of potential is

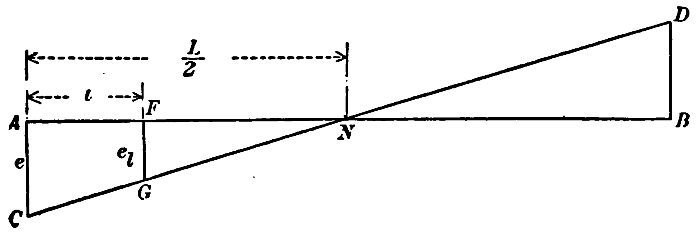


Fig. 2.

such that the rail is negative at the feeding point $A$ and positive at the point $B$, where the car is using power. In the middle there is a neutral point $N$. Let the potential difference between the rails and the earth at $A$ and $B$ be equal as shown in Fig. 2, wherein $AC = BD = e$. The potential difference decreases according to a fixed law in passing from $A$ to $N$, which decrease, for all practical purposes, may be taken as proportional to the distance.

* In the following discussions it is always assumed that the rail is connected with the negative bus bar, since this is generally true in practice. When the rails are connected to the positive bus the conclusions must be changed accordingly.

When $e_l$ is the potential difference at the distance $l$ from the feeding point $A$, then

$$e_l = \frac{e\,(L - 2\,l)}{L}.$$

The leakage of current in a certain length of track is dependent upon the potential difference between the rails and the earth and the resistance of the path. When $r$ is the mean resistance of the path per unit of length of rail, the leakage current at the end of the section (at $A$ or $B$) is

$$i_0 = \frac{e}{r}.$$

At $N$, in the middle of the section, there is no potential difference; therefore $e$ is also the potential difference between $A$ and $N$. When the current leakage is negligible we have

$$e = IR\frac{L}{2},$$

wherein $R$ is the mean resistance of the rail per unit length. In most cases the above formula gives the value of $e$ with sufficient accuracy.

If the leakage currents are taken into account, the value of $e$ will be smaller, and we have

$$e = pIR\frac{L}{2},$$

wherein $p$ is smaller than 1.*

From the foregoing, the leakage current per unit length at the ends of the section is given by

$$i_0 = pIR\frac{L}{2\,r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

This value also represents the maximum strength of the current leaving the rails.

* The drop in potential is given with more accuracy by the formula (8).

The current which leaves the rail at distance $l$ from the feeding point is,

$$i_l = \frac{e_l}{r} = \frac{e\,(L - 2\,l)}{L\,r},$$

$$i_l = pIR\frac{(L - 2\,l)}{2\,r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This formula is useful in estimating the strength of the leakage current at different points near the rails. Since the leakage current is proportional to the potential difference between the rail and the earth, the lengths $AC$ and $FG$ (Fig. 2), respectively, represent the leakage currents, as well as the potential differences between the rail and earth at the points $A$ and $F$.

The total leakage current for the length $l$ is therefore represented by the quadrilateral $AFGC$:

$$i = \frac{i_0 + i_l}{2}\,l,$$

$$i = pI\,\frac{(L - l)\,l}{2}\;\frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If only approximate results are desired, the factor $p$ may be taken equal to 1. Putting $p = 1$, formulas (2) and (3) become:

$$i_l = IR\frac{(L - 2\,l)}{2\,r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

$$i = I\frac{(L - l)\,l}{2}\;\frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad (3a)$$

When greater accuracy * is desired, $p$ may be calculated as follows:

* Accurate, mathematically derived formulas are obtained by solving differential equations, as is done in *E. T. Z*, 1895, p. 417. This calculation gives a catenary whose long chord is equal to the length of track and whose sag is equal to the value of the leakage current. See also *E. T. Z.*, 1902, p. 208.

$$pI = \frac{I + I_l}{2},$$

wherein $I$ is the current in the rail at the feeding point $A$ and $I_l$ the current in the rail at the point $F$.

Since, $I_l = I - i$, $pI = \frac{2I - i}{2}$,

and substituting this value in formula (3) and transposing we have,

$$p = \frac{1}{\frac{L - l}{4} l \frac{R}{r} + 1},$$

*i.e.*, a value which is very nearly 1, when $L$ and $\frac{R}{r}$ are not too great.

Substituting $\frac{L}{2}$ for $l$ we obtain the total leakage current in the section from $A$ to $N$, thus:

$$i_{max} = \frac{IL^2}{8} \frac{R}{r} = 0.125 \frac{IRL^2}{r} \quad . \quad . \quad . \quad . \quad (4)$$

Denoting the total rail resistance $LR$ by $R_l$ and the total resistance of the leakage path $\frac{r}{L}$ by $r_l$, we have,

$$i_{max} = \frac{I}{8} \frac{R_l}{r_l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4a)$$

*i.e.*, the total leakage current is proportional to the rail resistance and conductivity of the path from the rail to earth.

From measurements by Larsen and Faber * the leakage current was 15 amperes in a track 1,210 meters (3,970 feet) long, having a resistance of $210 \times 10^{-6}$ ohms per rail length [6 m. (19.68 ft.)] and carrying 100 amperes total. Assuming that the rail resistance is increased 50 per cent by the

* *E. T. Z.*, 1901, p. 1038.

joints, we obtain, in round numbers, 0.13 ohm per kilometer as the resistance of the leakage path. This value agrees well with values found in other places and by other methods, and therefore the above formulas give values which are sufficiently accurate in practice.

The current which remains in the rails is

$$I' = I - i.$$

At a distance $l$ (from the feeding point $A$) the current is

$$I' = I\left(1 - \frac{L - l}{2}\, l\, \frac{R}{r}\right) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

At the neutral point $N$ the rail current is a minimum. It is

$$I'_{min} = I\left(1 - \frac{L^2}{8}\, \frac{R}{r}\right) \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The potential difference between the earth and the rail decreases from the feeding point on; at the distance $l$ it is

$$e_l = \frac{IR}{2}\,(L - 2\,l) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

From the above calculations, for the simplest case of a single track section with only one car at the end of the section, it follows that the development of leakage currents is reduced:

1. When $R$ (rail resistance) is as small as possible, *i.e.*, when a heavy rail with well-bonded joints is used. The conductivity of the rail decreases with an increase in hardness of the metal. Thus it is seen that the conductivity of the metal should not be chosen so high as to affect the wearing qualities of the rail.

2. When $r$ (resistance of the leakage path) is as large as possible. The rails should be as well insulated from the ground as the local conditions permit. Pipe lines should not be laid too near the tracks. At places where the pipes

come very near the tracks the resistance $r_e$ will be very small. At such place currents are liable to flow to or from the pipes and can easily cause trouble by corrosion of the same. Places where the pipe systems come near the tracks should be carefully watched or protected by suitable insulation.

**3.** When the length of section $L$ is as short as possible. The leakage currents increase with the square of the length of the section between the point where the power is used and the feeding point. Therefore, there should be a large number of feeding points.

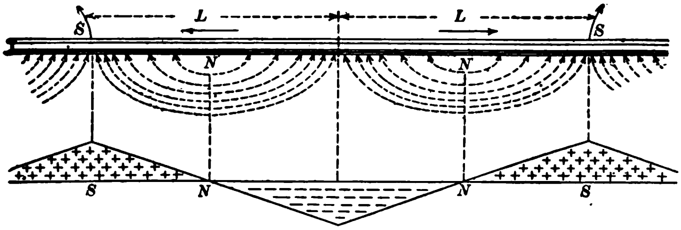


FIG. 3.

4. When the rail is lightly loaded. The current density in the rail must be kept low by properly locating the feeding points with reference to the switches, density of traffic, grades, etc.

When a section is fed in several points (Fig. 3), the distance $L$ is taken as one half the distance between two adjacent feeding points. The currents leave the rails at zones between the feeding points, re-enter them at zones about the feeding points; the zones between these are the neutral zones ($N$). For pipe lines which are electrically connected at the joints and run alongside the track, the zones near the feeding points are called danger zones. The distribution of potential with reference to the earth and rails between the two feeding points is shown in Fig. 3 (according to formula

(7)). At the feeding points the earth is positive to the rails, and midway between these points the earth is negative to the rails.

In judging the leakage currents the potential difference between the feeding points and between the feeding points and the points where the power is used come into consideration. The potential difference between the feeding points depends upon the feeding itself.

By proper conduction of the currents from the feeding points this potential difference may be held as small as desired. The drop in potential in the rails through the length $L$ would be $IRL$ if there were no leakage currents. Because of the leakage * the drop is,

$$E = IRL\left(1 - \frac{L^2 R}{12\,r}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Therefore, the greater the leakage the smaller the drop of potential in the rails. The potential difference between the feeding point and the neutral point ($N$, Fig. 2), also the potential difference between the feeding point and the earth ($e$), depend upon resistance $r$ of the path in the earth. Therefore, the measurement of these potentials can be used as a basis for estimation of leakage currents only in those cases where the resistance $r$ is known. In most cases, according to measurements made in different places, a mean value of the resistance $r$ can be used throughout the computations.

When the rail resistance, including that of the joints, is known, the resistance of the leakage path and the leakage current can be calculated from formulas (8) and (4) respectively, — assuming the rails to be continuous and without branches and that the same current is uniformly distributed throughout its length.

If the track makes a sharp curve, the resistance $r_e$ is

* *E. T. Z.*, 1895, p. 417.

somewhat decreased and the leakage currents accordingly increased. The density of the leakage currents in this case is given very approximately by formula (2).

Branch tracks, according to their location, may receive or send out currents. They increase the conductivity of the leakage path at those points. When near the feeding points they collect the stray currents from the earth; near the point where the power is used they give off currents to the earth; and at the neutral points they are indifferent. Branch tracks change the paths of the leakage currents in the earth and the location of the danger points.

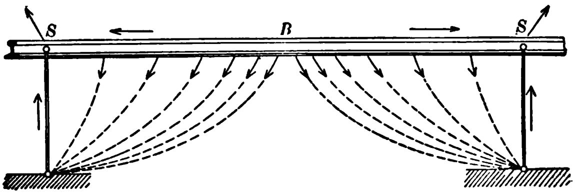


FIG. 4.

A thorough grounding of the rails at the feeding points, by connecting them to metal plates or pipe lines, draws the leakage currents from the rails throughout the entire length of the section (Fig. 4), there being no neutral points. If he ground is not perfectly made there will be neutral points; the more imperfect the ground the further the neutral point will be removed from the feeding point ($S$). In this way the return currents to the rails may be localized. However, the total leakage current will be increased in proportion as the resistance ($r$) of the leakage path is decreased; and although these currents be rendered harmless at certain fixed points, they may, on account of their increased density, do greater damage in other places.

Grounding the rails midway between the feeding points (as in $B$, Fig. 4), or placing pipe lines so near as to greatly decrease the resistance ($r$) of the leakage path, localizes and

increases the currents which leave the rails, and therefore distributes the returning currents over a greater length of track, broadening the danger zone and increasing the amount of damage done. Such conditions are rendered more fatal by the fact that the corrosion no longer takes place at those points in the pipe line which lie near the track, but at other points which are difficult and perhaps impossible to locate.

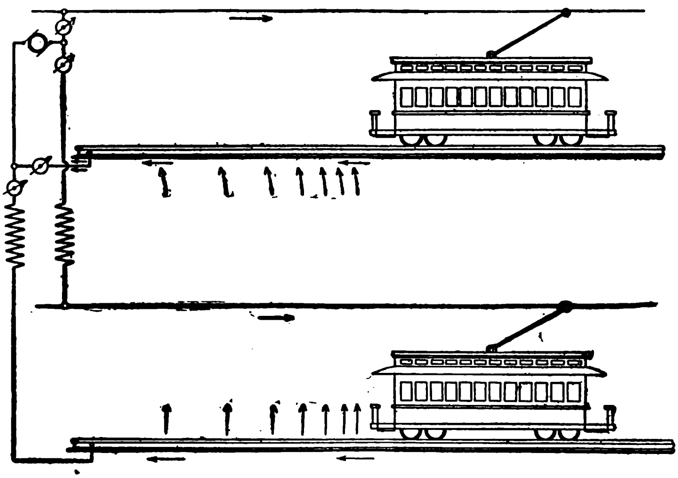

FIG. 5.

Bare returns, such as negative feeders from the rails, branch feeders from motors which are connected to the rails, etc., increase the conductivity to the earth, and therefore the leakage currents. When such feeders are laid parallel to the track the rail resistance is reduced, but unless the conductivity of the rails is increased to a greater extent than that of the leakage path, the leakage currents will be augmented. When such bare conductors lie deeper than the rails, their conductivity to earth, in spite of the small

surface in comparison to that of the rails, may come into consideration.

Bad joints increase the rail resistance and therefore the leakage currents. The nearer such joints are to the feeding points, the worse the bad effects, since the current density increases in the vicinity of such points.

Strong earth currents can be created by injudicious construction. For example (Fig. 5), two separate tracks fed from the same power house and laid out in such a way that the return of one is almost without loss of potential; while the other has considerable loss. In this case all the current will not return through the rails, but a part of it will leak across through the earth to the track which is nearer the power house. Putting ammeters in the trolley and return feeders of both lines, it is seen that the return of the farther line carries less current than that of the trolley, while the return of the nearer line carries more, thus showing the amount which leaks across through the earth. Such currents can be avoided by connecting the two lines to different machines.

# CHAPTER III

## STRAY CURRENTS WITH UNIFORMLY INCREASING CURRENT LOAD ON THE RAILS

On account of simplicity the conclusions given in the preceding chapter were deduced from formulas, which hold only in the cases where the rails carry a current uniformly distributed throughout their length. However, these conclusions also hold in the general case, where several cars are on the section at fixed distances from each other. In this case the current density increases as we approach the feeding points. Assuming that the increase in current density is uniform, that the current at the feeding point is equal to $I$, and that the current density midway between feeding points is zero, the current $I_l$ at the distance $l$ from the feeding point is

$$I_l = \frac{(L - l)\,I}{L},$$

wherein $L$ is half the distance between feeding points.

The rail resistance for the length $l$ is

$$R_l = lR,$$

wherein $R$ is the resistance per unit length. The potential drop per unit length in a certain point at a distance $l$ from the feeding point is

$$I_l R = \frac{I(L - l)\,R}{L}.$$

The total drop in the length $l$ is approximately

$$\frac{I + I_l}{2}\,lR,$$

or

$$E_l = \frac{I(2\,L - l)}{2\,L}\,lR \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The total drop (for $l = L$) is

$$E_L = \frac{ILR}{2} \quad \ldots \ldots \ldots (10)$$

Formula (9) can be simplified by taking the distances from the middle point instead of from the feeding point.

Thus, $x = L - l.$

Then the drop in the length $x$ is

$$E_x = \frac{I}{2}\frac{R}{L}x^2 \quad \ldots (9a)$$

This is the equation of the parabola, and therefore the drop increases from the middle point to the feeding point, according to that curve.

The potential difference between the rails and earth is a measure of the leakage. Plotting the drop in the length $L$

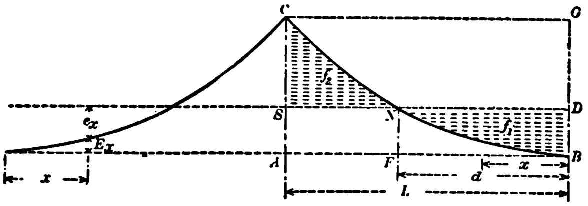


FIG. 6.

(Fig. 6) the curve $BC$ is obtained. For the sake of clearness the curve has been continued on past the feeding point ($A$). Let the earth potential be represented by the line $SD$, which is cut in the neutral point $N$ by the curve $BC$. Then $CS$ and $BD$ represent respectively the potential

of the feeding point and the middle point with reference to the earth. The leakage current at any point is proportional to the ordinate at that point measured from the axis $SD$. The area $BND = f_1$ represents the total leakage current from the section $BF$, and the area $CNS = f_2$ represents the total current which returns to the rails in the section $AF$. Therefore,

$$f_1 = f_2.$$

For the area of the figure $CBG$ we have

$$CBG = \tfrac{2}{3} AC \qquad AB = \tfrac{2}{3} L \qquad E_L = \frac{2}{3}\,\frac{IL^2R}{2},$$

and since

$$f_1 = f_2,$$

$$CBG = CSDG = DG \times AB = (E_L - E_d)\,L,$$

wherein $d = BF$, the distance of the neutral from the middle point $B$, and $E_d = NF$, the drop in the length $d$. From the formula (9$a$)

$$\frac{2}{3}\,\frac{IL^2R}{2} = \frac{IR}{2}\,(L^2 - d^2),$$

and

$$d = \frac{L}{\sqrt{3}}\,0.58\,L\,. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

*i.e.*, assuming the current density to uniformly increase as the feeding point is approached, the neutral point is situated at roundly six tenths of the length $L$ from the middle point $B$ or four tenths of the length $L$ from the feeding point.

The distribution of the current in the rail is changed by the leakage of current, and when these leakage currents are considered, the parabolic curve ($BC$), which represents the drop, is also changed. However, when the stretch between feeding points is not too great and the resistance ($r$) of the leakage path is not too small, that is, according to good

practice, the approximate values given by the above formulas are sufficiently accurate.*

* More accurate results may be obtained as follows: If current is fed to the rails throughout the entire length of the section (Fig. 7), then the total current fed in along the stretch $x$ is $\frac{x,I}{L}$ wherein $I$ is the current at the feeding point and $L$ the length of the section. Let the

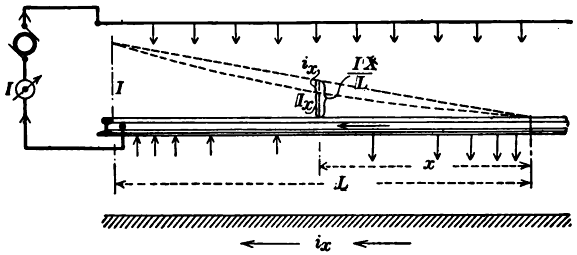


FIG. 7.

total leakage current from the stretch $x$ be $i_x$. Then the actual current in the rail is,

$$I_x = \frac{Ix}{L} - i_x,$$

and
$$dI_x = \frac{Idx}{L} - di_x.$$

The potential drop $dE$ in the infinitely short piece of track $dx$ is

$$-dE = I_x R dx,$$

$$\frac{dE}{dx} = -I_x R.$$

The current which strays from the length of track $dx$ is

$$di_x = (E - E_e)\frac{dx}{r},$$

wherein $E_e$ is the potential of the earth, $E$ that of the rail, and $r$ the resistance of the leakage path. From this we have

$$\frac{dE}{dx} = r\frac{d^2 i_x}{dx^2}.$$

The potential of the rails with reference to the earth is represented in Fig. 6 by the ordinates of the curve $BC$ laid

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Taking the second differential of the first equation

$$\frac{d^2 i_x}{dx^2} = -\frac{d^2 I_x}{dx^2}$$

Then we have the differential equation,

$$\frac{d^2 I_x}{dx^2} - I_x \frac{R}{r} = 0.$$

Solving,

$$I_x = C_1 \epsilon^{x\sqrt{\frac{R}{r}}} + C_2 \epsilon^{-x\sqrt{\frac{R}{r}}}$$

wherein $\epsilon$ is the base of the Naperian logarithm system. The constants $C_1$ and $C_2$ are determined by the limiting values of $x$.

For $\quad x = L, \quad I_x = I \quad$ and for $\quad x = 0, \quad I = 0.$

Substituting the values of the constants thus found,

$$I_x = \frac{\epsilon^{\sqrt{\frac{R}{r}}} - \epsilon^{-x\sqrt{\frac{R}{r}}}}{\epsilon^{L\sqrt{\frac{R}{r}}} - \epsilon^{-L\sqrt{\frac{R}{r}}}} I.$$

Expanding the numerator and denominator we obtain approximately

$$I_x = \frac{xI}{L} \frac{(6r + x^2 R)}{(6r + L^2 R)}.$$

and for the earth current,

$$i_x = \frac{Ix}{L} - I_x = \frac{Ix}{L} \frac{(L^2 - x^2) R}{(6r + L^2 R)}.$$

The highest value of $i_x$ occurs at the neutral point. Differentiating the last equation it is found that $x$ is a maximum for $x = \frac{L}{\sqrt{3}}$ (as in formula (11))

$$i_{max} = \frac{IL^2 R}{6r + L^2 R} \frac{2}{3\sqrt{3}} = \frac{0.384\, IL^2 R}{6r + L^2 R}$$

off from the earth potential line $SD$. For any point on the track at a distance $x$ from the middle point

$$e_x = E_d - E_x,$$

then from formulas (9$a$) and (11)

$$e_x = \frac{IR}{2L}\left(\frac{L^2}{3} - x^2\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

For a point $a$ the distance $l$ from the feeding point

$$e_l = \frac{IR}{2L}\left(\frac{2L^2}{3} + l^2 - 2Ll\right) \quad . \quad . \quad . \quad . \quad (12a)$$

From these two equations the potential of the feeding and middle points can be obtained, thus,

$$e_{l=0} = \frac{IRL}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Earth positive to the rail.

$$e_{l=L} = -\frac{IRL}{6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Earth negative to the rail (Fig. 3).

From this it is seen that the potential difference between the rail and earth is twice as great at the feeding point as at the middle point. The potential at the feeding point is about two thirds, and that in the middle point about one third of the potential lost in the whole section $L$.

Of course the above values of potential between rails and earth do not hold true when a network of tracks with single branches running out from it has a feeding point within the network. The branches lower the resistance ($r$) of the leakage path. Therefore, within the network the potentials are reduced, while those at the end of the branches are correspondingly increased.

The current which leaves the rail along a short length $a$ at the distance $x$ from the middle point is $\frac{e_x A}{r}$ and the total

leakage current along the entire length $x$ is given by the areas $f_1$ or $f_2$ which are bounded by the lines $BD$ or $CS$, $SD$, a portion of the curve $BC$ and the ordinate corresponding to the point $x$. This area is made up of a rectangle $e_x x$ and a portion of a parabola $\frac{2}{3} E_x x$. We have

$$i_x = (\tfrac{2}{3} E_x + e_x)\frac{x}{r},$$

or substituting the corresponding value

$$i_x = \frac{IRx\,(L^2 - x^2)}{6\,Lr} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The total leakage current (corresponding to the area $f_1$ or $f_2$) is, for

$$x = \frac{L}{\sqrt{3}}.$$

$$i_{max} = \frac{IRL^2\sqrt{3}}{27\,r} = 0.064\frac{IRL^2}{r} \quad . \quad . \quad . \quad (16)$$

For pipe lines which lie parallel to the track and have good electric joints, the danger zone extends from the feeding point to about four tenths of the distance $L$ ($L =$ half the distance between feeding points). The danger zone is shown in Fig. 6 by the area $f_2$.

In places where there is a complicated network with several feeding points, the danger zones are located about the feeding points. The density of the earth current increases as the feeding point is approached, and is very small near the neutral point. The total leakage current must pass the neutral zone, but it is so widely distributed that the density is low, this being especially true in the vicinity of the rail.

The direction of the current in the earth is greatly influenced by the conductivity of the soil, masses of metal, etc., so that in large cities where there are complicated pipe systems laid in the earth, it is exceedingly difficult to for-

mulate a law for its determination. In general, it may be said that the currents near the feeding point are directed toward the rail, those near the point midway between the feeding points away from the rail, and those in the neutral zone parallel to the rail and toward the feeding point.

If the rail is connected to the positive bus, the danger zone is shifted from the feeding point to the portion midway between the feeding points. In this case the danger zone is larger, but the potential with reference to the earth is lower (about half its former value, formulas (13) and (14)).

Comparing the formulas (4) and (16) for the maximum value of the leakage current a great difference in the coefficients is noted, 0.125 in the case where one car is located at the end of the section and 0.064 when the cars are uniformly distributed along the section. This difference is explained by the fact that the current from the cars near the feeding point has but a short distance to go and the leakage currents increase as square of the distance of the car from the feeding point. Thus it is seen that the amount of leakage depends upon the distribution of current throughout the section.

# CHAPTER IV

## RESISTANCE VALUES

In order to use the foregoing formulas, it is necessary to know something of the different resistances. Values, whose application is general, cannot be given, because they depend upon the materials used in the construction and local conditions. For this reason values given in the literature differ greatly. In that which follows the values are only approximate.

The rail resistance depends upon the character of the metal. We have hardness and wearing qualities on one side and conductivity on the other. According to the hardness and the chemical composition the conductivity varies from 4 to 8; however, the material with the conductivity 8 is almost too soft to be used for rails. The harder the material the lower the conductivity. Therefore, for mechanical reasons the lower conductivity must be included in the bargain. V. Gaisberg gives * the mean resistance of 0.00003 ohm for a steel rail, 1 meter (3.28 feet) long, 6464 square millimeters (10 square inches) cross-section, and at a temperature of 29° C. (84.2 F.). This corresponds in round numbers to the conductivity 5. The values 5 or 6 may be taken as general in application where ordinary rail material is used. Neglecting the joints the resistance of 1 kilometer (0.62 miles) of single track is 0.015 ohm, and that of 1 kilometer of double track 0.0075 ohm. Kallmann † gives the average resistance of 1 kilometer of double track of Phœnix rails XIV *a.* or XIV *f.*, as 0.0075 ohm. The total resistance is increased by the resistance at

* *E. T. Z.*, 1903, p. 492.

† *E. T. Z.*, 1899, p. 163.

the joints.* According to the rules of the Verband Deutscher Elektrotechniker, concerning the protection of pipe lines from stray currents of street railways (Sec. 6), the joints must be so made that the resistance of a line of single track will not be increased more than 0.03 ohm per kilometer by the joints. According to V. Gaisberg the joints can be so made that no appreciable increase in the resistance results. In practice, the conductivity of the fish-plate joint cannot be depended upon, so it is neglected in the calculations and that of the copper bonds considered alone. The above value of 0.03 ohm per kilometer may be taken as a maximum value for single track with no bad bonds. Ulbricht † gives the resistance of a double track including joints as 0.01 ohm per kilometer. Rasch ‡ gives 0.019 ohm as the resistance of 1 kilometer single track, neglecting the bonds (rails 30 kilograms per meter or 60 pounds per yard). This value corresponds to a conductivity of 6.5. In calculating the resistance of the joints Rasch assumes a resistance of 0.0002 ohm per contact for the bolts. Including the bonds the resistance of 1 kilometer of single track would be increased by about 0.023 ohm.

The resistance of the path from the rail to the pipes in Berlin soil is given by Kallmann § as 0.1 to 0.2 ohm per kilometer of double track. These values include the surface resistance $r_s$ and the soil resistance $r_e$. Ulbrich§§ gives a surface resistance $r$ of 0.2 ohm and a soil resistance of

* Recent investigations in Germany showed that the conductivity of rail joints varies greatly, increasing the total resistance of the track up to 100 per cent in some cases. The electrically welded and thermit joints, however, were found excellent, possessing in many cases the conductivity of the rails themselves. — TRANSLATOR.

† *E. T. Z.*, 1902, p. 212.

‡ Bell-Rasch Strom Verteilung für Elektrischer Bahnen, 1898, p. 26.

§ *E. T. Z.*, 1899, p. 167. §§ *E. T. Z.*, 1902, p. 214.

0.1 ohm per kilometer. These values vary with local conditions. In cities with complicated pipe systems which at certain points come quite close to the rails, the resistance of the leakage path can become comparatively small. The discrepancies between the various values given by different persons are great. Wietlisbach* gives the resistance offered to leakage currents to the earth as 15 to 20 ohms per kilometer. Rails in sandy soil offer greater resistance to leakage currents when the sand is dry than when it is moist. The insulation of the rail plays an important part. Interurban roads with a special roadbed can have such a high resistance that no appreciable leakage takes place.

The distribution of the current in the earth depends upon the resistance of the soil ($r_e$). Clean sand and rock have a very low conductivity. The resistance of a cubic meter of moist sand varies from 100 to 1,000 ohms, according to the amount of salt present. Fleming † gives 15 ohms for clay soil. V. Gaisberg ‡ points out that the sprinkling of salt on the rails for melting the snow greatly decreases the earth resistance and aids electrolysis.

Dirty water as found in the street has, according to Rasch, a resistance of 10 ohms per cubic meter. For ordinary city water the resistance was found to lie between 3 and 80 ohms. This shows that rivers help very little in carrying the stray currents. The resistance of the soil is of less importance when the currents can distribute themselves over a great area.

Mortar and concrete has, according to Lindeck § a resistance of 0.7 ohm per cubic meter. The conductivity is great in comparison to that of the soil. Therefore, the development of stray currents is aided to a certain extent when the rails are buried in concrete. According to Schie-

* Schiemann, Bau ü Betrieb Elektrischer Bahnen 1, p. 132 (1900).

† Electrician 41, p. 689 (1898). ‡ *E. T. Z.*, 1903, p. 492.

§ *E. T. Z.*, 1896, p. 180.

of the path from the rails to the pipes haracter and the diameter of the pipes. 0,2 ohm per kilometer. By a careful insulating paint the resistance of the e greatly increased. A coating of ce- is a conductor, does not increase the does it protect the pipe. After a pipe n for a time its surface becomes covered which is a poor conductor and conse- the resistance ($r$). V. Gaisberg states of great protection to cast iron pipes.

mann, asphalt concrete, which is waterproof, is a better insulator, so that a thin layer of asphalt concrete greatly increases the resistance offered to the leakage currents.

The total resistance of a pipe line is made up of the resistance of the pipe and that of the joints. Ulbricht assumes a resistance of 0.02 ohm per kilometer for a 20 centimeter (8 inch) pipe. The resistance of the joints may become very high after being buried a long time. Meng * experimented upon some joints which had been in the earth from twenty to forty years. In gas pipes he found the joint resistance to lie between 0.08 and 1,200 ohms, the mean of which is about 230 ohms; in water pipes he found resistances between 0.02 and 115 ohms or a mean of 14 ohms. It was also found that the conductivity was little affected by filling the pipes with water.

Therefore, the water within the pipes takes little part in carrying the current, and electrolysis on the inner wall is little to be feared, since the current does not leave the metal to enter the water. This is very fortunate, for should the water take an important part in carrying the current, the pipes would become corroded at the point where the currents enter as well as where they leave.

From measurements made by Larsen and Faber † the conductivity of English cast iron pipes is approximately 1. A 9 inch pipe with a wall $\frac{3}{8}\frac{3}{4}$ inch thick (*i.e.*, 26 centimeters outside diameter) had a resistance of $96.10^{-6}$ ohms per meter, or 0.1 ohm per kilometer, neglecting the joints.

Values given by Lubberger ‡ agree well with those of Faber, namely a 100 millimeter (4 inch) pipe had a resistance 0.00028 ohm per meter. For joints he found resistances from 0.00072 to 0.076 ohm. He also found § that water in the pipes had little effect upon the resistance.

* *E. T. Z.*, 1901, p. 354. † *E. T. Z.*, 1901, p. 1038.

‡ *Journal für Gasbeleuchtung ŭ Wasserversorgung*, 1901, p. 508.

§ *Journal für Gasbeleuchtung ŭ Wasserversorgung*, 1901, p. 723.

The resistance ($r$) of the path from the rails to the pipes depends upon the character and the diameter of the pipes. Ulbricht assumes 0.2 ohm per kilometer. By a careful application of an insulating paint the resistance of the leakage path can be greatly increased. A coating of cement, since cement is a conductor, does not increase the resistance ($r$) nor does it protect the pipe. After a pipe has laid in the earth for a time its surface becomes covered with a layer of rust which is a poor conductor and consequently increases the resistance ($r$). V. Gaisberg states that this is a source of great protection to cast iron pipes.

## CHAPTER V

### DISTRIBUTION OF POTENTIAL IN THE EARTH

STRAY currents enter pipe lines only when there are potential differences between the earth and the pipes. Therefore, it is very desirable to know the distribution of potential in the earth, so as to be able to follow the path of the currents. The distribution of current and potential in the earth depends principally upon conditions along the track (current density in the rails, rail resistance, surface resistance, distance ($2L$) between feeding points), and also upon conditions in the earth (resistance of the soil). The location and character of the ground water and above all the location, extent, and conductivity of the pipe systems also exert a strong influence. In large cities with complicated networks of pipes and tracks, it is very difficult to form an idea of the distribution of the stray currents without making a thorough set of tests. This problem is rendered so much the more difficult when there are several systems of railways operated from different power houses, and so interlaced that currents from one can flow in the other throughout a portion of the way.

If the ground water or the pipe line were nearly without resistance, there would be no appreciable potential in their vicinity. In fact, however, as was shown in the foregoing chapter, such lines may have very high resistances. Therefore, the surface resistance ($r_s$), the soil resistance ($r_e$) and the pipe resistance ($R_p$) all come into consideration in determining the current which will flow in the pipes (Fig. 8). In calculations made by Ulbricht the soil resistance $r_e$ was particularly considered. If the currents flowing in the

pipes are not large and the pipe resistance is small, a mean value can be used, which is designated as the potential of the earth or the pipe. In general this potential corresponds to that of the neutral point in the track. Therefore, instead of the potential between a point and the pipe, the potential between the point and the neutral point may be used. Therefore, in the following computations the potential with reference to the neutral point, the pipes, or the earth, will be taken as the same, and designated as potential with reference to standard earth.

Ulbricht * has throughly investigated the distribution

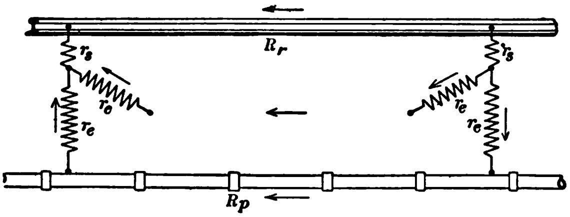


FIG. 8.

of stray currents in the earth, both theoretically and by practical measurements. From this investigation it is possible to determine distribution of potential in the earth. The knowledge of the distribution of potential near the feeding points is especially desirable, since it is at these places that the pipes are mostly damaged. Ulbricht calculated the potential values for a double track road 4 kilometers (2.5 miles) long; feeding points at the ends; full width of tracks 4 meters (13 feet); current at each feeding point 100 amperes, and rail resistance 0.01 ohm per kilometer.

The potential, with reference to standard earth at the feeding point, from formula (13) ($I = 100, R = 0.01, L = 2$), is 0.67 volts. At different distances $\delta$ from the track the following values are obtained:

* *E. T. Z.*, 1902, pp. 212 and 720.

| $\delta$ | Potential with Reference to Standard Earth. |
|---|---|
| 0 m. | 0.67 volts |
| 20 " | 0.38 " |
| 200 " | 0.13 " |
| 2000 " | 0.0045 " |

From this it is seen that the potential decreases rapidly with increase of distance from the rail. Constructing the equipotential curves, by drawing continuous lines through points of the same potential, it is seen that the curves cling closely to the track. Fig. 9 shows the curves for the above example. The distortion of the curves by systems of pipes is not considered. There is a difference of 0.1 volt between the neighboring lines. The dotted line represents a potential 0.05 volt with reference to the standard earth.

*S* is the feeding point, *N* the neutral point, and *B* the middle point. The length *SB* equals 2 kilometers. The distances perpendicular to the rails are laid off to the same scale as those along the rails. In the vicinity of the feed-

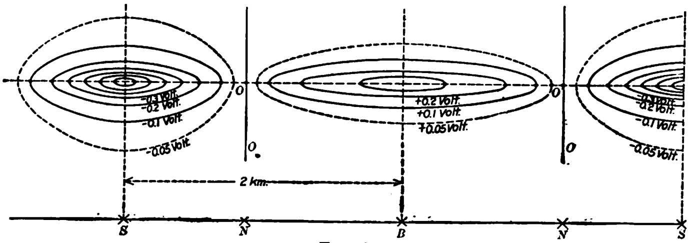


Fig. 9.

ing points the earth is negative to the standard earth, and midway between the feeding points it is positive. The potential at *S* is $-$ 0.67 volt, and at *B* $+$ 0.33 volt. The various curves close upon themselves about the feeding

points and the middle point ($B$). If a good conducting pipe line is so laid as to cut, say, three of the potential lines, then the maximum potential in the earth at the pipes would be 0.3 volt, regardless of whether the lines cut belonged to the system about the feeding point or to that about the middle point ($B$). Therefore, the danger risk of the pipes can be estimated by the number of lines cut by them.

These curves can be greatly distorted by pipe systems, which are so connected as to be good conductors, since, for example, the potential of distant points can be brought to points near the track.

In railway systems with a great number of feeding points, the theoretical neutral points do not have the same potential, except when the return feeders are so arranged that no appreciable difference of potential exists between the feeding points. When it is impossible to so arrange the feeders that no potential differences exist between the feeding points, the values obtained from formula (11) for determining the position of the neutral point are no longer correct. The neutral zones where there is no potential with reference to standard earth are displaced, because the potential of standard earth is influenced by the feeders. Let it be assumed that the track is fed at four points $S_1$, $S_2$, $S_3$, $S_4$, (Fig. 10). If the drops in the various feeders are equal, then the potential along the track with reference to the earth will vary according to the equation of a parabola (Fig. 6), and the neutral points will be located at $N$.

Should the current taken at $S_3$ be decreased and that at $S_2$ and $S_4$ correspondingly increased, the neutral points would be moved farther from the feeding points and the danger zones increased in size. The potential at the feeding points $S_2$ and $S_4$ with reference to standard earth will be increased, while that at $S_3$ will be decreased.

In general we have the following: the potential at and

near a feeding point with reference to standard earth is increased by an increase in the draft of current and *vice versa.* From this it follows that it is possible to a certain extent to change the potential and thus the danger zones, so as to reduce the risk of damage to the pipes at certain points along the tracks. It must be remembered, however, that a reduction of potential at any one point results in a corresponding increase in potential at some other point.

In practice it would be too much to expect to obtain a very accurate estimate of the distribution of the potential before the road is built, but the potential at points where the danger risk is greatest should be determined.

According to Ulbricht,* assuming that the resistance of

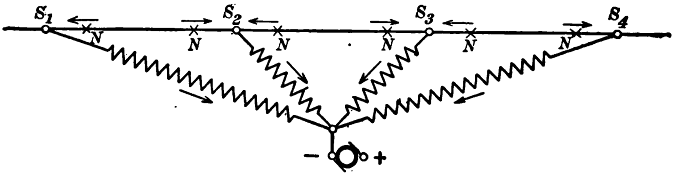


FIG. 10.

the leakage path is uniform, the approximate potential in points at different distances from the feeding point may be calculated from the following formula when the distance is not too great.

$$e_\delta = \frac{e_0}{1 + b\delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

wherein $e_\delta$ is the potential of the point with reference to standard earth at the distance $\delta$ (in meters) from the feeding point, $e_0$ is the potential at the feeding point (formula (13)), and $b$ is a constant which may be taken as approximately equal to 0.1. Substituting for $e_0$ the value found in formula (13) we have

* *E. T. Z.*, 1903, p. 690.

$$e_\delta = \frac{IRL}{3(1 + 0.1\,\delta)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (17a)$$

Since the potential decreases rapidly as the distance from the track increases, the V. D. E.* code states that a metal pipe system whose nearest point is 1 kilometer from the tracks is without risk. Under favorable conditions, however, the pipes may come still nearer without incurring an appreciable risk. According to the V. D. E. code, metal pipe systems are considered as out of danger when they lie between two lines, which converge toward the track, making an angle of 30° with the same, and whose points of intersection are not so far from each other that a potential of 0.3 volt is exceeded at any point between them when the average current is assumed to flow in the rails.

Such mean current is calculated for the year and includes the time during the night when the cars do not run. When the cars run only sixteen hours per day the actual potential would be 0.45 volt. From this it follows that pipe systems lying within the hatch-lined section (Fig. 11) are considered as out of danger. This assumes that in a direction perpendicular to the track no potential of more than 0.3 volt exists. The potential is not measured between points on the rails, but between points $A$ and $B$, right close to them. The potential between the corresponding points on the rails is higher, because drop occurs through the surface resistance. It is further assumed that not only between the end points $A$ and $B$, but between any two points between $A$ and $B$, the maximum potential is not exceeded.

For instance, if there is a pipe near the feeding point $S_2$ (Fig. 10) between the points $NN$, then the potential between the end points $NN$ is zero, while that between $N$ and $S_2$ can exceed the maximum, and the pipe be thus subjected to a risk.

* *Verband Deutcher Elektrotechniker.*

Pipes which run perpendicularly across the tracks are considered out of danger when the potential drop in the earth along the pipes between the nearest and farthest points from the track does not exceed the standard 0.3 volt. At the farthest point the potential is generally that of standard earth.

It is difficult to trace the potential distribution in the earth when several interlacing railway systems are fed from separate power houses. The resultant effect is found by superposing the effects of each single system. If the

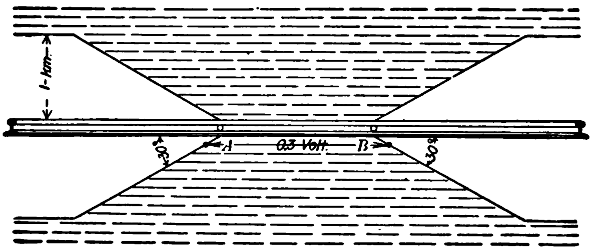


FIG. 11.

feeding points of the different systems are near to each other, the harmful current may be taken as approximately equal to the sum of the stray currents of the different systems.

If the feeding points of two railway systems are so located that the feeding point of one lies midway between those of the other, the result is a more favorable distribution of the potential, since the effect of the one reduces the size of the danger zone of the other. If of two large systems the one has a better return circuit with various feeding points, while the other has but one feeding point, potentials of considerable value may be avoided in the rails of the first by properly locating the feeding points.

# CHAPTER VI

## CORROSION CURRENTS

A PART of the current which strays from the rails returns again without having entered any pipes or other metallic masses. Such currents are harmless in the earth. They cause corrosion of the rails themselves. The only harmful

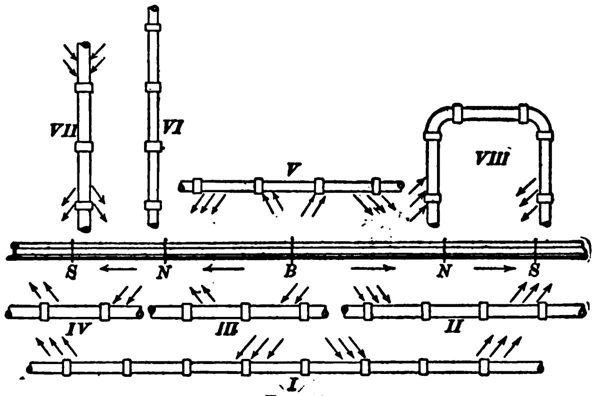


FIG. 12.

stray currents are those which enter and leave metallic masses that are buried in the earth. These currents may be designated as corrosion currents. Pipe lines with good electric joints carry these currents when the surrounding earth has a potential above standard earth, *i.e.*, when the pipe line cuts the equipotential curves (Fig. 9). This is generally true whether the pipes are in the danger zone or not. The direction of the current at any given point is determined by the polarity of the potential in the earth at that point.

Fig. 12 shows the direction of the currents in several arrangements of pipes with reference to the track. The pipe line *I* runs parallel to the track from one feeding point (*S*) to the next (*S*). The leakage currents enter that portion of this pipe line which lies between the neutral points *NN* and leave near the feeding points *SS*. The line *II* runs from the middle point *B* to the feeding point *S* at the right. The currents enter in the vicinity of the middle point *B* and leave near the feeding point *S*. The lines III and IV run parallel to the tracks, but only extend from middle point to neutral point and from neutral point to feeding point, respectively. In both cases the currents enter that part which is farthest from the feeding point and leave that which is nearest. In the line V, which extends from neutral point to neutral point, the currents enter at the middle and leave at the ends. Pipe line VI runs perpendicular to the track across the neutral point and carries no current whatsoever. Line VII, which runs parallel to line VI, but cuts across the danger zone, gathers currents at distant points and gives them up inside the danger zone. Line VIII is perpendicular to the track at the neutral point, but runs into the danger zone. The currents enter near the neutral point and leave inside the danger zone. From this it is seen that the term danger zone applies only to those pipe systems which run parallel to the tracks throughout the length of the section.

At great distances from the tracks the earth has the same potential as the neutral point (standard earth). Pipe lines which extend to a great distance from the tracks behave in same manner as though they started at the neutral point. If these pipes enter the danger zone (line VIII, Fig. 12), they collect currents at a distance and deliver them to track. If they enter the zone about the middle point *B*, they collect currents at that point and deliver them at a distance.

If extensive and complicated pipe systems send branch lines into the danger zone a great deal of current may be collected and given off to the track, thus incurring great risk to the branch lines. The above statements are true only in those cases where the pipes are so connected as to be good conductors.

It is difficult to calculate the intensity of the current flowing in a pipe system. Assuming that the drop in the earth parallel to the track varies, according to formula (9*a*), which assumption is only approximately true, we have

$$e_x = c\frac{I}{2}\ \frac{R}{L}x^2.$$

($x$ is measured from the middle point $B$ and parallel to the track.) $c$ is taken smaller than 1. According to the formulas of Ulbricht, $c$ decreases as the distance from the track increases. Neglecting the resistance of the pipes and assuming that the pipes have the same potential as the neutral point, the potential in the earth with reference to the pipes is found from formula (12).

$$e = c\frac{IR}{6\,L}(L^2 - 3\,x^2).$$

The total current entering or leaving the pipes within the section $x$ is obtained from formula (15)

$$i_p = c\frac{IRx}{6\,r_pL}(L^2 - x^2),$$

wherein $r_p$ is the resistance of the path from the pipes to earth.

The maximum current in the pipes is $\left(\text{for } x = \frac{L}{\sqrt{3}}\right)$

$$i_p = \frac{cIRL^2\sqrt{3}}{27\,r_p} \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

($c$ depends upon the resistance $r_p$).

Since $c$ decreases as the distance from the rail increases, the danger risk of pipes must be reduced in the same pro-

portion. In the above example of a two-track road with a distance of 4 kilometers between feeding points, the resistance of the leakage path being 0.2 ohm per kilometer, the formula (16) gives the stray current as

$$i_s = 1.28 \text{ amp.}$$

If the resistance from the pipes to earth is also 0.2 ohm per kilometer, when the distance from the tracks is 20 meters (65.8 feet) we obtain

$$i_p = 0.73 \text{ amp.}$$

In reality the pipe current is smaller, since in the calculation the pipe resistance and the effects of the pipes upon the distribution of potential were neglected. The less the resistance from pipes to earth the greater the latter influence. And for this reason formula (19) does not hold for small values of $r_p$.

Ulbricht * calculates that $\frac{110}{147}$ or about three fourths of the total leakage current enters a pipe, which lies two meters from the track. Larsen and Faber † in Copenhagen, found that about half of the leakage currents were carried in the pipes.

More accurate calculations ‡ in which the pipe resistance

* *E. T. Z.*, 1902, p. 212. † *E. T. Z.*, 1901, p. 1038.

‡ Let $x$ be the distance of the pipe from the track, $d_p$ ithe current, $E_s$ the potential in the pipe, $e^s$ that in the earth near the pipe, $R$ the rail resistance and $R_p$ the resistance of the pipe per unit length; then,

$$di_p = \frac{(e_x - E_x)\,dx}{r_p}.$$

If $E_s$ is the potential of standard earth

$$di_p = \frac{[(e_x - E_s) - (E_x - E_s)]\,dx}{r_p},$$

$$E_x - E_s = \frac{cIR}{6L}(L^2 - 3x^2),$$

$$de_x = \frac{-cIRx\,dx}{L},$$

since

$$dE_x = -i_pR_pdx,$$

is considered conduct to a formula similar to formula (18). From this the current in the pipe is

$$i_p = \frac{cIRL^2\sqrt{3}}{27 r_p\left(1 + \frac{L^2}{6}\frac{R_p}{r_p}\right)} \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Putting the pipe resistance $R_p = 0$, we obtain formula (18).

The maximum potential in the earth near the pipes is

$$E = \frac{cILR}{2}.$$

---

we have,

$$\frac{d^2 i_p}{dx^2} = \frac{de_x - dE_x}{dx\, r_p} = -\frac{cIRx}{r_p L} + i_p \frac{R_p}{r_p}.$$

The solution of the differential equation gives

$$\frac{cIRx}{r_p L} - i_p \frac{R_p}{r_p} = b_1 \epsilon^{x\sqrt{\frac{R_p}{r_p}}} + b_2 \epsilon^{-x\sqrt{\frac{R_p}{r_p}}},$$

wherein $\epsilon$ is the base of the Naperian system of logarithms.

The constants $b_1$ and $b_2$ are obtained by substitution of limiting values of $x$

for $x = 0$ we have $i_p = 0$,

and for $x = L$ we have $i_p = 0$.

Substituting we have,

$$i_p = \frac{cIRx}{LR_p} - \frac{cIR}{R_p}\,\frac{\epsilon^{x\sqrt{\frac{R_p}{r_p}}} - \epsilon^{-x\sqrt{\frac{R_p}{r_p}}}}{\epsilon^{L\sqrt{\frac{R_p}{r_p}}} - \epsilon^{-L\sqrt{\frac{R_p}{r_p}}}}.$$

Expanding, we have approximately,

$$i_p = \frac{cIRx\,(L^2 - x^2)}{L\,(6\,r_p + L^2 R_p)},$$

and for

$$x = \frac{L}{\sqrt{3}}$$

the maximum value is $$i_{max} = \frac{cIRL^2\sqrt{3}}{27\, r_p\left(1 + \frac{L^2}{6}\frac{R_p}{r_p}\right)}.$$

Substituting this value in formula (19) we obtain,

$$i_p = \frac{2\,LE\sqrt{3}}{27\,r_p\left(1 + \frac{L^2}{6}\frac{R_p}{r_p}\right)} \quad . \quad . \quad . \quad . \quad . \quad (19a)$$

In the above-mentioned example, in which the current was calculated from formula (18) to be 0.73 ampere, by using formula (19) 0.44 ampere is obtained.

From this it is seen that in considering the resistance of the pipe much smaller values of current are obtained.

The foregoing calculations hold in cases where the pipes are so connected as to be good conductors. The pipe currents decrease with an increase of pipe resistance. If short lengths of insulating material are introduced in the pipe line the currents will be greatly reduced, providing such pieces are close enough together.

## CHAPTER VII

### CORROSION CURRENTS WHICH DO NOT COME FROM RAILWAYS

From the foregoing it is seen that in railway systems, when the rails are used for return, the leakage currents and therefore the pipe currents, can never be completely eliminated. However, it has often happened that cases of corrosion have been laid to leakage currents from railways when in reality such was not the case. The natural earth currents and telegraph currents are scarcely to be considered. Reactions set up by the galvanic currents resulting from the connection of several different metals in the earth, play a more important part. Strong earth currents can come from faulty cables. Assume that there be several insulation faults on the negative conductor of an extensive cable system. This is easily possible, since, as is well known, it is more difficult to keep up a perfect insulation of the negative than of the positive conductor.

Supposing, now, that the positive conductor becomes grounded by a blow from a pick-axe, then current will flow from this place to all the faulty places in the negative conductor. The sheath, which is connected with the positive conductor at the fault, takes on the potential of the positive conductor and gives off current throughout its entire length. The greater the length of the sheath and the higher the potential, the greater these earth currents and their effects. First of all, the sheath will be damaged throughout its entire length. When the sheaths are insulated from each other at the joints the leakage currents are kept in one length of sheath. If the fault is not discovered it takes

but a short time to ruin the cable. The sheath of cables laid near the faulty one may take on the dangerous potential by contact and also be destroyed. Such cases of corrosion are recognized as not coming from railway leakage currents, because they are local, and because great differences of potential are found in the earth that cannot be accounted for by leakage from the tracks. The cable itself is most endangered by such leakage. This sort of corrosion may be avoided by maintaining a good insulation and by immediately repairing all grounds, especially of the positive conductor.

## CHAPTER VIII

### CORROSION

THE decomposition of metals in the earth takes place at that point where the current leaves the metal to enter a chemical reacting conductor (electrolyte). Several experiments were made in studying this subject. Boxes 1 meter long were filled with earth, and some contained small amounts of different salts. The current was supplied through copper plates (Fig. 13), a constant potential of 2 volts being maintained between them. The earth was kept moist and

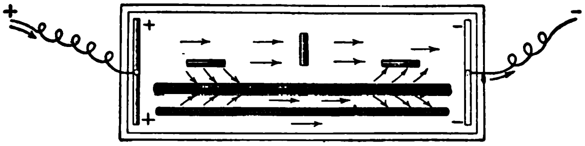

FIG. 13.

controlled by a special mechanism. In the earth there was an iron pipe, a piece of armored cable, and different pieces of cable sheath. As a control simultaneous experiments were made with boxes in which no current was introduced. After the boxes had stood several months the iron pipes in the boxes to which current was supplied were found to be badly corroded, commencing at the middle and extending toward the negative plate, while on the other end there was not the slightest sign of corrosion. The pipes in the other boxes were but slightly corroded and the corrosion was uniformly distributed throughout their entire length. Therefore, the current on leaving the pipe had had a strong corroding effect, and upon entering had had a protecting effect

(hydrogen coating). The protected cable sheath (jute covered) showed no trace of corrosion. The pieces of sheath were all corroded, their position in the box being immaterial. The side turned toward the negative plate was always corroded. Naturally the positive copper plate was also greatly decomposed.

The decomposition of iron in an electrolyte is about 1 gram per ampere hour.

This value holds only under the assumption that the earth is a perfect electrolyte. When the salty moisture in the soil is not the only conductor, but the soil itself takes part in the conduction of the current, the earth does not act just like an electrolyte * and only a part of the current works to decompose the pipe. This theory, which was formulated by Claude †, was not confirmed by Larsen ‡ in his experiments.

According to Larsen's laboratory experiments the total current which leaves the metal to enter the earth works to decompose the metal. It was found that approximately 1.10 grams § of metal was decomposed per ampere hour, independent of the current density, the voltage, the kind of iron, the amount of sodium chloride, and of whether the circuit was continuously closed or periodically opened and closed.

From this it is seen that the current density at the point where the current leaves the pipe is a measure of the corroding effect. In general the decomposition, as given by the developed formulas, is spread over a fairly large area. However, in special cases the current density can become quite great. This is the case, for example, when the cur-

* *E. T. Z.*, 1902, p. 69. † *Eclairage Electrique*, 1900, p. 141.

‡ *E.T.Z.*, 1902, p. 841.

§ Kinckling found that 1 ampere per second would decompose 20 pounds of iron and 70 pounds of lead per year. *Municip. Jour. and Engr.*, Vol. XV, p. 97 (1903).

rents which have been collected in an extensive system of pipes are given off in the danger zone by single branch pipes. The damage done comes quicker to notice when pipes which are well insulated from the earth are at certain places in good connection with the earth. At such places the current comes out with a greater density, and deep, narrow holes are eaten in the pipes.

When the current enters the pipes from the earth polarization potentials are developed, the values of which, according to Larsen, depend upon the working potentials. Assuming the soil to be the same at the points where the current enters and leaves, the polarization potentials at the

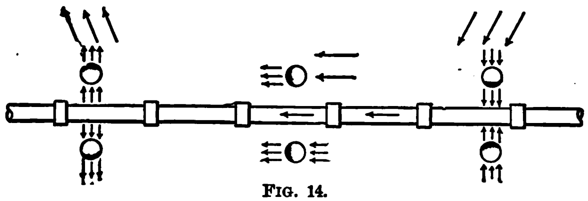

FIG. 14.

entering and leaving points are equal and opposite in sign, so that they cancel each other. From this it follows that very low potentials are sufficient to send current through the pipes, since they are, in general, not opposed by the polarization potentials. In this the painstaking experiments of Fleming,* those of Larsen, and the above-mentioned ones with the boxes, where small pieces embedded in the earth were corroded, agree.

Small plates or spheres of an easily decomposed metal buried in the earth near the pipes form a convenient method of locating currents of great density and obtaining their direction. Such plates or spheres will be corroded on the side where the current leaves them (Fig. 14).

* *E. T. Z.*, 1898, p. 835.

The chemical character of the soil plays an important part in corrosion, in that it affects the conductivity and, therefore, the current density. V. Gaisberg * observed that the electrolytic effects were increased by the presence of salt in the soil. Salt, which is put on the rails to melt ice, dissolves in the water and filters out into the soil, unless this is prevented by a good waterproof coating of asphalt or other paving material.† Soluble chlorides come most often into consideration in cases of corrosion. By electrolysis the salts which occur in the earth, as sodium chloride and calcium chloride, are made to give up free chlorine. This free chlorine reacts strongly with iron and forms chloride of iron, which covers the pipe with a layer of rust. If there is any water present, iron hydroxide is formed and chlorine is again set free and can once more react with the iron and so on. After the chlorides come the sulphates. Because of their more difficult solubility, especially of sulphate of lime, they are more difficult to decompose and come less into consideration. Next in order come the nitrates. The organic salts have no influence worth mentioning, also the silicates and carbonates have little influence on electrolysis.

Many different metals become corroded by the action of earth currents. The corrosion takes place in various ways,

* *E. T. Z.*, 1903, p. 492.

† From experiments made at Wisconsin University, Professor Jackson deduced: 1. Corrosion is due to secondary chemical reactions, brought about by electrolysis of some salt held in solution by the water, and not by the direct oxidation resulting from the electrolysis of water.

2. Corrosion takes place at a rate which depends solely upon the current strength in the pipes and the nature of the salts present in the soil.

3. Small quantities of salt are sufficient to start the reactions when current flows, and the reactions once started are regenerative and continue as long as the current flows. *Electrical World*, Vol. XXVIII, p. 684.

according to the character of the surface, and according as the electrolytic action is stimulated by direct chemical action. Cast iron is attacked * to a less degree than wrought iron. Lead pipes are always corroded.

According to the formulas the entrance of current into the metallic masses, and, therefore, the amount of corrosion, depends, not only upon the potential near the pipes, but also upon the surface resistance and the ordinary resistance of the metallic mass. Therefore, bare metals suffer more than those which are protected by a layer of insulation.

Pipe lines which have been buried in the earth for a long time become rusted, thus raising the surface resistance and the resistance at the joints, and in this way help to protect themselves.

It is a mistake to assume that high resistance at the joints of a pipe line causes excessive corrosion at those places. This could only be true when the surface resistance was very small and the soil resistance very great.

Assuming, for example, a surface resistance of only 0.1 ohm per kilometer, or 100 ohms per meter, and neglecting the soil resistance, the current would have to overcome a resistance of 400 ohms in passing around a joint, if the current left and returned within a half a meter on each

* See V. Gaisberg, *E. T. Z.*, 1903, p. 493, and Schiemann, Bau und Betrieb Elektrischer Bahnen 1, 148 (1900). That wrought iron is more liable to damage from rust than cast iron, as is often stated, is disputed. See Verhandlungen des Vereins für Beförderung des Gewerbefleisses. Report of January 4, 1904. Professor Dr. Freund, in Frankfurt a. M., made extensive experiments with cast iron pipes, which were badly corroded, and wherein it was not determined whether the corrosion was brought about by stray currents or by local currents set up by contact of particles of graphite with iron in presence of moist earth.

Digest from Zeitschrift für angewandte Chemie, 1904, in the *Journal für Gasbeleuchtung und Wasserversorgung*, 1904, p. 232. See also p. 509.

side of the joint. In order to send only 0.01 ampere around the joint it would be necessary to expend 4 volts. Thus it is seen that the increasing of resistance at the joints is not only harmless but is, in fact, to be recommended. The V. D. E. code states that pipe lines with high resistance

FIG. 15.

joints are not in danger of corrosion. By insulating the pipes at the joints the currents are forced around the joints (Fig. 15). Only in special cases (high soil resistance, low surface resistance) does corrosion occur at such joints.* Joint insulation has proved especially advantageous in

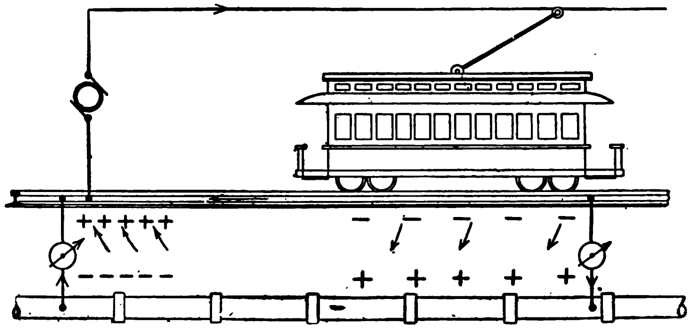

FIG. 16.

cable construction for avoiding corrosion. Cases have been observed where the cable armor was corroded (caused by faults) only to the insulated joints, the rest of the armor remaining intact.

Insulating coverings always protect, because insulated

*Journal für Gasbeleuchtung ŭ Wasserversorgung*, 1903, p. 955.

cables which lie close to the tracks are seldom harmed. The danger risk for pipes increases as they near the tracks. At points where pipes come very near the track, special precautions should be taken to prevent corrosion.

At the entering and leaving point of pipe currents polarization potentials are developed. During the time the cars are running the earth currents flow as shown in Fig. 16, but when the cars stop running, providing a polarization potential has been developed, the current flows in the opposite direction, as shown in Fig. 17. Voltmeters con-

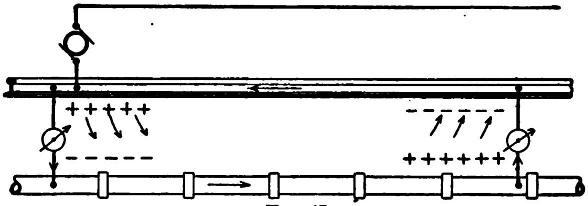

FIG. 17.

nected across from rail to pipe show the same direction of current in both cases.

The polarization potentials behave the same as two primary batteries connected in series by means of the pipes and the tracks. The potentials can be measured while the cars are running and after they have stopped, and thus the existence of polarization potentials and their values can be determined. The polarization currents, which flow when no cars are running, since they are opposed to the leakage currents, can slightly reduce the latter.

According to Larsen's experiments it makes no difference with the corrosion effect whether the current flows steadily or intermittingly. And, therefore, there would be no appreciable reduction due to polarization.

According to Lubberger, * beside the stray currents in the

**Journal für Gasbeleuchtung und Wasserversorgung,* 1901, pp. 508 and 723.

pipes there were currents of nearly a constant value which continued to flow after the cars had stopped running. While the cars are running the stray currents are superposed upon these constant currents, which Lubberger says are set up by the E.M.F.'s in the joints. Corrosion is caused by these constant currents independent of the leakage currents.

Naturally the rails also become corroded and to a far greater extent than the pipes, since only a part of the stray currents enter the pipes. Therefore, if the rails are found to be badly corroded, it is positively known that there is considerable leakage.

The danger zones for the pipes do not coincide with the places where the rails corrode, which statement follows from the formulas developed in the foregoing chapters. When rails which have lain near the middle joint (between the feeding points) for several years, show but slight traces of corrosion, it may be safely assumed that the pipes in that section are not exposed to danger from stray currents. The density of the current leaving the rails can be determined from formula (12). For a section of the length $a$ at a distance $x$ from the middle point the leakage current is

$$\frac{e_x a}{r} = \frac{IRa}{2\,Lr}\left(\frac{L^2}{3} - x^2\right).$$

At the middle point ($x = 0$) with $a = 1$ meter and $r$ the resistance of the leakage path per kilometer the current is

$$\frac{IR\,0.001\,L}{6\,r}.$$

Any metallic masses, such as iron constructions, which are not insulated from the earth are liable to corrosion. The corrosion effects depend upon the length throughout which the structure is electrically connected, and also upon local conditions which may cause considerable potential

differences between the structure and earth, such that currents flow from the metal to the earth. Cables, as was before mentioned, are sufficiently protected by their insulation, when they are not brought too near the tracks and when the armor is insulated at the joints. If for any reason, as for example in high-pressure cables, the electrical connection of the sheaths desired, the cable should be laid at a greater distance from the tracks.

# CHAPTER IX

## MEASUREMENTS

By calculation it is possible to obtain an idea of the probable distribution of the leakage currents and locate the places where there is danger of corrosion, either in a projected or an existing road. However, the actual conditions can be more nearly approached by practical measurements; but, nevertheless, practical measurements without a thorough knowledge of the system, the location of pipes, the conductivity of the pipes, etc., help but little in determining the danger of corrosion at the different points.

The measurements * which are desirable in estimating the danger of corrosion are rail potentials, earth potentials, leakage current, and current in the pipes.

The distribution of potential in the rails while the cars are running is measured most conveniently by using stranded pilot wires. The potential between the feeding points indicates whether the feeders are in proper working order. The potential between the middle point (midway between feeding points) and the feeding point indicates the highest potential which can occur in the earth. The measurement of this potential, while the cars are running, is difficult, since generally there are no pilot wires run to the middle points. It suffices to determine this value from time to time. Without a knowledge of the soil resistance these values serve to no purpose in determining the earth currents, since from formula (8) it is seen that the greater the conductivity of the soil the less the drop in the rails.

* These measurements are minutely discussed by Kallmann in a lecture given January 24, 1899. (*E. T. Z.*, 1899, p. 163.)

The determination of the distribution of potential in the earth serves as a good basis for judging the danger risk of pipes, because the greater the potential near the pipes the greater the risk. In general it is amply sufficient to make the measurements only in those places where from local conditions it is seen that there is liable to be trouble.

According to the V. D. E. code, in such measurements metallic rods are to be used as electrodes and allowances made for their surface resistance, which can be done, for example, by using a variable resistance in series with the voltmeter. The distribution of potential and current in the earth should not be changed, and in order to avoid this, high resistance voltmeters should be used.* The measurements should be repeated as soon as possible after the cars stop running, at the same time bearing in mind that the measurements can still be influenced by polarization effects at the rails and pipes. In order to fix the districts wherein, according to the V. D. E. code, there is no danger to pipes, the potentials in the earth close to the rails and pipes must be measured.

In making these measurements the electrodes should be placed at about 10 cm. to one side of the rail-base or pipes and driven into the earth to the same level as that of the rails or pipes.

Potential measurements between track and pipes can be used in determining the polarity and the danger zones. In estimating the danger risk of pipes they have no value except that the pipe be continuously a good conductor. For short pieces of pipe or long lines which are not electrically connected, these measurements have absolutely no worth in estimating the value of the current in the pipes.

* Rowland notes that widely different potential readings may be obtained by using voltmeters of different resistances. When no current flows, the potential may be electrostatic. *Amer. Elect.*, Vol. IX, p. 156 (1897).

Short pieces of pipe (Fig. 18) take on the potential of the surrounding soil. They are positive, neutral, or negative to the rails according to their distance from the feeding point and carry currents, whether they are located near the middle point, the neutral point, or the feeding point.

In any case the potential measurements between the rails and pipes give qualitative and not quantitative results concerning the danger risk, since the corrosion depends upon the density of the current * as it leaves the pipe. This density in turn depends, among other things, upon the potential of the pipe with reference to the surrounding earth and the surface resistance. The resistance ($r$) of the leakage path is not contained in the formulas (7) and (12)

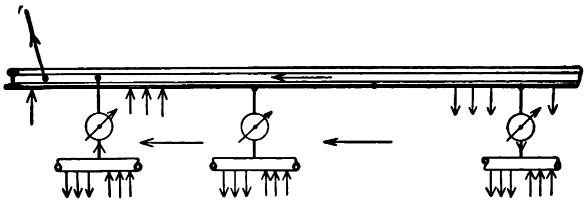


FIG. 18.

for computing the potential between the track and the pipes. This potential depends solely upon the track length, the track resistance, and the track current. From this it is seen that the corrosion currents are not determined by these potentials alone.

In order to calculate the current leakage from the track, the resistance of the latter must be known. If it is possible to disconnect a section of several hundred meters from the rest of the system, connect the ends of the rails by cross bonds and send a constant current (storage battery) through the thus insulated section. The track re-

* Lubberger, *E. T. Z.*, 1902, p. 186.

sistance can be determined from current and potential measurements. By measuring the drop in short sections the leakage of current may be determined. Disconnecting the section in the middle and inserting an ammeter (Fig.

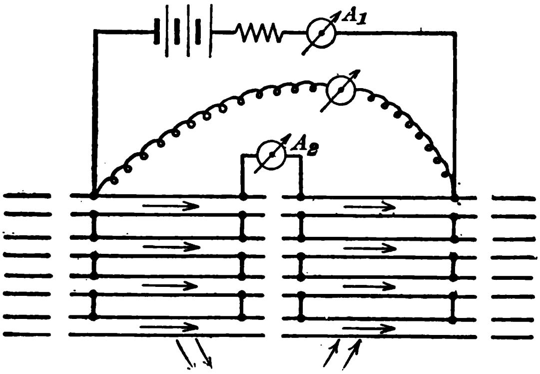


FIG. 19.

19), the difference between the readings $A_1$ and $A_2$ gives the value of current which strays into the earth.

This method of determining the leakage currents is not

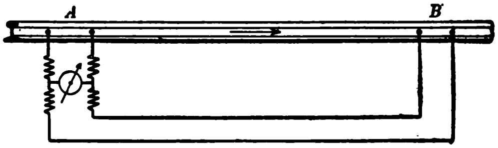


FIG. 20.

accurate, because the resistance of the track is considerably increased by the insertion of the ammeter. Thus the measurements made by this method give too large values of leakage.

Kallmann * gives a differential method which is more

* *E. T. Z.*, 1899, p. 163, and 1898, p. 683.

accurate. The principle is seen from Fig. 20. Let it be required to determine the leakage in the section $AB$. Voltmeter leads are brought from each end and the voltmeter so connected that the difference in drop in the two sections (of about 10 meters long) at $A$ and $B$ is measured.

When the resistances are carefully adjusted with a constant current flowing, the voltmeter can be used to read amperes leakage, and if the apparatus is carefully calibrated, it may be used while the cars are running. It is assumed that there are no rail crossings or branches between the points $A$ and $B$, and that during the measurements there is no car in the section between $A$ and $B$. At the points $A$ and $B$ the rails must be thoroughly cross bonded.

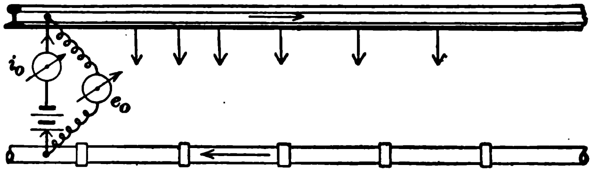


FIG. 21.

In large railway systems with many feeding points it suffices to determine the leakage in certain places by the use of Kallmann's method. Then if the rail resistance is known, the current $I$ in the rail can be determined, and by substitution in formula (4) for the maximum leakage current ($i_{max}$) the resistance ($r$) of the leakage path can be obtained.

The resistance ($r$) of the leakage path can be indirectly obtained from formula (8), when $I$ and $R$ and the drop $E$, which would occur in the track if there were no leakage, are known.

The resistance ($r$) can be measured directly, when the section is disconnected from the rest of the track and the

rail and pipe resistances are known, by connecting a battery between the track and the pipes (Fig. 21) and measuring the total current and E.M.F. Assuming that the leakage decreases uniformly as the distance from the feeding point increases, if the maximum current is $i_0$ the mean current is $\frac{i_0}{2}$. When the rail resistance per unit length is $R_r$, that of the pipe $R_p$, the drop in the pipe and rails up to the end of the section $L$ is

$$\frac{i_0 (R_r + R_p) L}{2}.$$

From this, the potential difference between the pipe and the track is

$$e_0 - \frac{i_0 (R_r + R_p) L}{2},$$

wherein $e_0$ is the E.M.F. of the battery.

The mean potential difference is

$$\frac{4 e_0 - i_0 (R_r + R_p) L}{4}.$$

The mean current per unit length flowing from the rails to the pipes is, therefore,

$$\frac{4 e_0 - i_0 (R_r + R_p) L}{4 r},$$

and the total current leaving the section $L$ is

$$\frac{[4 e_0 - i_0 (R_r + R_p) L] L}{4r},$$

which is equal to the current $i_0$ and we have

$$i_0 = \frac{4 e_0 L}{4 r + L^2 (R_r + R_p)} \quad . \quad . \quad . \quad . \quad (20)$$

A more accurate * calculation gives

$$i_0 = \frac{e_0 L}{r} \frac{6r + L^2(R_r + R_p)}{6r + 3L^2(R_r + R_p)} \quad . \quad . \quad . \quad (20a)$$

For example, setting $e_o = 2$ volts, $L = 2$ km., $r = 0.2$ ohm, $R_r = 0.01$ ohm, and $R_p = 0.1$ ohm, from formula (20) we have $i_o = 12.9$ amperes, while formula (20*a*) gives $i_o = 13$ amperes.

---

* Let $E_l$ be the potential of a point in the track at the distance $l$ from the feeding point, and $e_l$ the corresponding pipe potential, then the current flowing from the rails to the pipe in the length $dl$ is

$$di = (E_l - e_l)\frac{dl}{r},$$

and

$$\frac{d^2i}{dl^2} = (dE_l - de_l)\frac{1}{r}.$$

But

$$dE_l = iR_r dl,$$

and

$$de_l = iR_p dl,$$

wherein $i$ is the current in the rails and in the pipe at the distance $l$.

Writing the differential equation

$$\frac{d^2i}{dl^2} - i\left(\frac{R_r + R_p}{r}\right) = 0,$$

the solution,

$$i = b_1 \epsilon^{l\sqrt{\frac{R_r + R_p}{r}}} + b_2 \epsilon^{-l\sqrt{\frac{R_r + R}{r}}}.$$

Setting

$$\sqrt{\frac{R_r + R_p}{r}} = a,$$

we have

$$i = b_1 \epsilon^{la} + b_2 \epsilon^{-la}.$$

Determining the constants from the limiting values of $l$.

$$l = 0, \quad \frac{di}{dl} = \frac{e_0}{r},$$

$$l = L, \quad i = 0.$$

For first equation we have,

$$\frac{di}{dl} = b_1 a \epsilon^{al} - b_2 a \epsilon^{-al}.$$

For

$$l = 0,$$

$$a(b_1 - b_2) = \frac{e_0}{r},$$

and for

$$l = L,$$

$$b_1 \epsilon^{aL} + b_2 \epsilon^{-aL} = 0,$$

The value $r$ can be obtained from formulas (20) or (20$a$) when the other quantities are known.

If the current is not fed into the track at the end, as in Fig. 20, the current $i_0$ is made up of two components, one flowing toward each end. If the current is fed in at the middle of the section and $L$ is equal to half the section length, then the value of $i$ obtained from formula (20) is twice its real value. The same reasoning holds for cases where the current is introduced at crossing or branching points. From formulas (20) or (20$a$) the currents must be separately calculated for each branch starting from the feeding point.

If the rail and pipe resistance are neglected in formulas (20) and (20$a$), the values of $i$ obtained are too large (in the above example 20 amperes instead of 13). In the same way, since from formula (20)

$$r = \frac{e_0 L}{i_0} - \frac{L^2 (R_r + R_p)}{4} \quad . \quad . \quad . \quad . \quad (21)$$

too large values of $r$ would be obtained if the rail and pipe resistances were neglected.

---

and we have,

$$b_1 = \frac{e_0}{ar} \frac{\epsilon^{-La}}{\epsilon^{La} + \epsilon^{-La}},$$

$$b_2 = \frac{e_0}{ar} \frac{\epsilon^{La}}{\epsilon^{La} + \epsilon^{-La}}.$$

Substituting these values

$$i = \frac{e_0}{ar} \frac{\epsilon^{(l-L)a} - \epsilon^{(L-l)a}}{\epsilon^{La} + \epsilon^{-La}}.$$

The only value which concerns us is,

$$i_0 = \frac{e_0}{ar} \frac{\epsilon^{-La} - \epsilon^{La}}{\epsilon^{La} + \epsilon^{-La}}.$$

Neglecting the sign of $i_0$ and expanding, we have approximately,

$$i_0 = \frac{e_0 L}{r} \frac{6r + L^2 (R_r + R_p)}{6r + 3L^2 (R_r + R_p)}.$$

If, according to Herrick,* the rail is connected through a resistance to the pipes, the current passing from one to the other depends not only upon the rail and pipe resistance, but also upon the resistance of the leakage path and the distribution of current in the rails.

Therefore, without knowing the first, it is impossible to determine the resistance of the path from the current and potential measurements. If the track at the feeding point is connected directly to the pipes (Fig. 22), current will pass from the track to the pipes throughout the entire section, and the greatest density will occur at the point

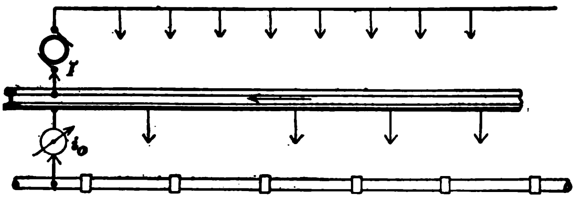


FIG. 22.

midway between feeding points or the end of the section. If the decrease in current carried by the rails is proportional to the distance from the feeding point, and the current at the feeding point is $I$, then the mean track current is $\frac{I}{2}$, the drop in the section $L$ (neglecting the leakage currents) is $\frac{ILRr}{2}$, and the current flowing through the connection with the pipe at the feeding point is $i_o$. Since the pipe current at the end is zero (assuming that the effect of connecting the rail and pipe does not extend beyond the end of the section $L$, midway between feeding points), the mean pipe-current is $\frac{i_o}{2}$ and the drop in the pipes $\frac{i_oR_pL}{2}$.

* *Street Railway Journal,* 1898, p. 775.

From this it follows that the potential difference between the pipes and track at the end of the section $L$ is

$$\frac{IR_rL - i_0R_pL}{2}.$$

The mean potential difference between the track and pipes, since the potential at the feeding point is zero on account of the short circuit, is

$$\frac{IR_rL - i_0R_pL}{4}.$$

The mean leakage current per unit length is

$$\frac{IR_rL - i_0R_pL}{4r}.$$

The total leakage in the section $L$ is

$$\frac{IR_rL^2 - i_0R_pL^2}{4r} = i_0.$$

Simplifying,

$$i_0 = \frac{IR_rL^2}{4r + R_pL^2} \quad \ldots \ldots \quad (22)$$

A more accurate calculation * gives

* Let $E_x$ be the potential of a point in the track and $e_x$ that of the pipe at a distance $x$ from the middle point. For the current passing over to the pipe the following is true:

$$\frac{di}{dx} = \frac{E_x - e_x}{r},$$

$$\frac{d^2i}{dx^2} = \frac{1}{r}\left(\frac{dE_x}{dx} - \frac{de_x}{dx}\right),$$

$$dE_x = - I_xR_r\,dx,$$

$$de_x = - iR_p\,dx.$$

If the current in the rails at the distance $x$ is $I_x$, then

$$I_x = \frac{Ix}{L} - i.$$

Wherein $I$ is the current at the feeding point.

$$i_0 = \frac{IR_r}{R_r + R_p}\left(1 - \frac{1 + L^2\dfrac{R_r + R_p}{6r}}{1 + L^2\dfrac{R_r + R_p}{2r}}\right).$$

---

We have,

$$\frac{d^2i}{dx^2} - \frac{iR_r}{r} + \frac{IxR_r}{Lr} - \frac{iR_p}{r} = 0.$$

Putting
$$i\,(R_r + R_p) - \frac{IxR_r}{L} = u,$$

we obtain,

$$\frac{d^2u}{dx^2} - u\,\frac{R_r + R_p}{r} = 0.$$

From this

$$u = b_1\epsilon^{xa} + b_2\epsilon^{-xa}$$

wherein
$$a = \sqrt{\frac{R_r + R_p}{r}}.$$

Substituting for $u$,

$$i\,(R_r + R_p) - \frac{IxR_r}{L} = b_1\epsilon^{xa} + b_2\epsilon^{-xa}.$$

The constants can be determined from the limiting value of $x$

for
$$x = 0, \quad i = 0,$$

and for
$$x = L, \quad \frac{di}{dx} = 0.$$

Differentiating,

$$\frac{di}{dx}(R_r + R_p) = \frac{IR_r}{L} + b_1a\epsilon^{xa} - b_2a\epsilon^{-xa} = 0.$$

$$b_1 = -b_2 \text{ and } b_1 = -\frac{IR_r}{La\,(\epsilon^{La} + \epsilon^{-La})}.$$

$$i\,(R_r + R_p) - \frac{IxR_r}{L} = -\frac{IR_r(\epsilon^{xa} - \epsilon^{-xa})}{La\,(\epsilon^{La} + \epsilon^{-La})}.$$

Expanding and solving for $x = L$, we have approximately,

$$i_0 = \frac{IR_r}{R_r + R_p}\left(1 - \frac{1 + L^2\dfrac{R_r + R_p}{6r}}{1 + L^2\dfrac{R_r + R_p}{2r}}\right).$$

Formulas (22) and (22*a*) give almost the same results; for example, taking $I = 100$, $R_r = 0.01$, $R_p = 0.1$, $L = 2$, $R = 0.2$, formula (22) gives $i_1 = 3.3$ amperes and formula (22*a*) gives $i_o = 3.27$ amperes.

If the current is not distributed as was assumed in the derivation of the formulas, different values are obtained. Thus, if there is only one car on the section $L$, and that at the end, we have,

$$i_0 = \frac{IR_rL^3}{2r + L^2(R_r + R_p)}.$$

If the distribution of current load in the rails is not accurately known, the measurements can give only a general idea of resistance of the leakage path.

If the current at the feeding point comes in from two or more branches (Fig. 23), the formula (22) may be applied to each branch. When the feeding point receives current from two equal sections which are equally loaded, the formula (22) holds true, if $I$ is the total current leaving the track at the feeding point and $i_o$ the total current flowing in the connection between the feeding point and the pipes.

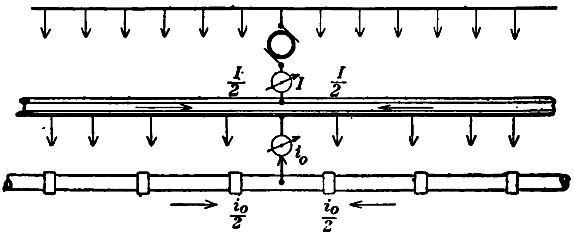


FIG. 23.

The rail resistance, neglecting that of the joints, is best determined in the laboratory. The resistance of a constructed track may be determined, by choosing a section, which is not too long and which is disconnected from the rest of the system, and measuring the drop in E.M.F. when

a constant current is flowing. It is a good plan when making such measurements to also take the drop in short sections and then from formulas (3a) and (4) the leakage current can be computed and allowed for.

Bad joints increase the track resistance and are conducive to current leakage. The locating of badly bonded joints is generally done by comparing the resistance of the joint with that of a certain length of rail, the measurements being made with a differential galvanometer.*

The Siemens and Halske apparatus for measuring the resistance of rail joints is shown in Fig. 24. The handle $A$

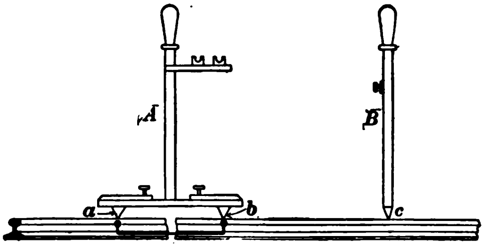


FIG. 24.

carries the instrument and at its lower end is provided with two adjustable copper contact points $a$ and $b$ which are made to span the joint; the handle $B$ has one contact point $c$, and is placed on the rail about 4 meters from the joint. The galvanometer (Deprez d'Arsonval), which is protected from magnetic disturbances and reads in milli volts is connected with the contact points as shown in Fig. 25. If the contacts $a$ and $b$ are placed on the joint while the road is in operation, current will flow in one coil of the galvanometer and the drop will be indicated; now if the contact $c$ is also placed on the rail, current will flow in the other coil which tends to decrease the reading, and by adjusting the

* *E.T.Z.*, 1900, pp. 796 and 986, and 1901, p. 84.

contact *c* the galvanometer needle can be brought to zero. Then the resistance of the rail length *bc* is equal to that of the joint, and if the rail resistance is known, that of the joint can be given in ohms. The measurements are independent of the current load in the rails, but they can be more accurately obtained when large currents are flowing.

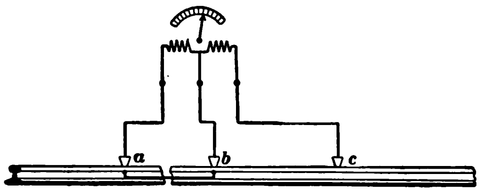


FIG. 25.

The measurement of pipe currents is generally difficult. Larsen and Faber,* in Copenhagen, determined the pipe currents by measuring the pipe resistance at night when the road was out of operation and then measuring the

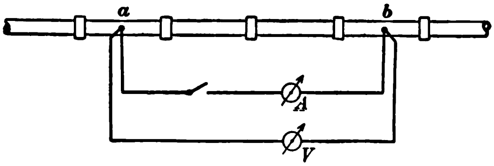


FIG. 26.

potential drop in the same pipes in the daytime, with very sensitive galvanometers. By making such measurements at different points, and having a good idea of the local conditions, the danger zones can be fairly well mapped out.

Since the pipe currents are proportional to the track currents, a few simultaneous measurements of track and pipe currents are sufficient to establish the ratio.

According to Herrick,† the pipe current can be approxi-

* *E. T. Z.*, 1901, p. 1038. † *Street Railway Journal*, 1898, p. 775.

mately determined from two potential and one current measurement. Leads are brought from the pipe line at $a$ and $b$ (Fig. 26) and a voltmeter and ammeter connected across. The voltmeter current is considered negligible in comparison with the pipe current $I_p$. With the switch open, the potential $e_1 = I_pR_p$, and with the switch closed, the potential is $e_2$, and the current $i$. Then,

$$e_2 = (I_p - i)\,R_p.$$

Then if the current in the pipes has not changed in value during the measurements

$$I_p = i\frac{e_1}{e_1 - e_2}.$$

In order to account for possible polarization potentials the measurements are repeated after the cars stop running.

According to Lubberger,* in addition to leakage currents constant currents flow in the pipes, and continue to flow when the road is not operating. Such currents are set up by polarization, E.M.F., or by galvanic action at the joints. When the road is in operation the stray currents are superposed upon these constant currents. In order to obtain a clear idea of this phenomenon and to be able to judge the danger risk of pipes, Lubberger recommends that potential measurements be made between two hydrants before and while the road is in operation. In order to obtain the pipe current from these measurements the pipe resistance is determined when the cars are not running. Lubberger used apparatus as shown in Fig. 27, wherein a battery is connected across the hydrants $a$ and $b$. The battery current $I$ divides; one part, $I_1$, flows from $b$ to $a$, taking the shortest path, while the other part, $I_2$, flows past the hydrant $c$ and through the system back to $a$. If the corresponding

* *Journal für Gasbeleuchtung u. Wasserversorgung,* 1901, pp. 508 and 723.

resistances pro unit length are $R_1$ and $R_2$, the lengths $L_1$ and $L_2$, then $I_1R_1L_1 = E_1$ and $I_2R_2L_2 = E_2$ and $I = I_1 + I_2$. If it is assumed that the resistance is proportional to the length ($R_1 = R_2$), we have,

$$R_1 = \frac{E_2L_1 + E_1L_2}{IL_1L_2}.$$

(In the same manner Larsen determined the resistance, except that the current was sent through a short portion of the pipe.) If the hydrants are too far apart, or the pipe

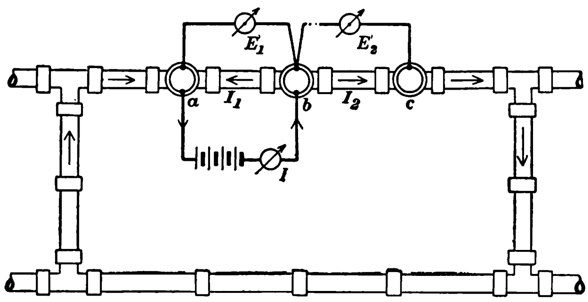


FIG. 27.

resistance too great, so that appreciable leakage takes place, the above equations cannot be used in determining the resistance of the pipes. If the pipe resistance is known, the pipe currents can be obtained by measuring the E.M.F.'s between *a* and *b* and *c* while the cars are running. In making connections to the hydrants, care must be taken to make a proper connection, because the hose couplings are often insulated from the hydrant by rubber or leather packing.

Lubberger also used the method shown in Fig. 26, but found somewhat varying values. For example, with method shown in Fig. 27, he found the resistance of 1 meter of pipe to be 0.007 and 0.0021 ohm, with method of Fig. 26

he found 0.004 and 0.0012 ohm; for the same pipe. According to this, determinations of the pipe current by the method shown in Fig. 26 would give too small values. Lubberger measured the pipe currents before and while the road was in operation. He found that the current in the pipes, while the cars were running, averaged about four times and in one case 16 times that which flowed when no cars were running. According to Lubberger, the difference of these currents is a measure of the risk to the pipes.

## CHAPTER X

### PREVENTATIVE MEASURES

In order to reduce or remove the danger of electrolytic action, measures are taken to reduce the stray currents, to make their entrance in the pipes more difficult and their departure take place with the least possible amount of damage to the pipes. Leakage currents can be completely eliminated only when uninsulated rails are not used for carrying return currents; for example, storage battery cars, lines with double overhead trolley lines, or two conductor conduit systems. These systems are all expensive, the storage battery car is not practical, and double overhead trolleys and two conductor conduit systems are difficult to construct and maintain, especially where there are many crossings.*

In the formulas for the value of the leakage current or the pipe current, the rail resistance, the length of section, and the current in the rail appear in the numerator ; the surface resistance, the soil resistance, and the pipe resistance in the denominator. Thus it is seen that, in general, to reduce the danger risk, the quantities in the numerator must be made as small as possible and those in the denominator as large as possible.

* In Washington the conduit system with complete metallic circuit is used in the city and the double trolley outside, and in Cincinnati the double trolley is used throughout. Neither of these cities has been troubled with electrolysis. The borough of Manhattan, N. Y. also uses the two conductor conduit system on the surface lines, but there is some leakage from the elevated lines and a great deal of current comes over from Brooklyn through the Brooklyn bridge, enters the pipes, and returns through the Williamsburg bridge and the river. — TRANSLATOR.

In order to obtain low track resistance, the largest possible rail section should be used and the joints should be well bonded. In order to insure good conductivity of the track, the rails, and in double-track roads the tracks should be cross bonded at fixed intervals.

According to the V. D. E. code, every tenth rail of a single track should be cross bonded; and in double-track roads the tracks should be cross bonded at every twentieth joint. Increasing the conductivity of the rail, by connecting a copper conductor in parallel with it, is to no purpose, except when the conductor has a large cross-section. Assuming a medium conductivity of four for the track including the bonds, the cross-section of the copper conductor must be $\frac{1}{14}$ that of the rail in order to reduce the rail resistance, and therefore the leakage currents, to one half their normal value.

For a double-track road, and rails of 6,464 square millimeters cross-section, it would be necessary to use a copper conductor of about 1,800 square millimeters cross-section, in order to obtain any results worth while. Therefore, it is better to use heavy rails and keep the bonds in perfect condition. In order to increase the total conductivity of a system, and to avoid high potentials at the crossing points, the rails should be thoroughly bonded at the crossing points and switches. As to the sort of bonds to use and the method of application reference should be had to the extensive literature on that subject.

Just as the track resistance is to be kept low, the pipe resistance is to be increased as much as possible. The conductivity of the pipe material cannot greatly influence its choice, because there are other factors which determine that. Cast iron has a higher specific resistance than wrought iron, and for this reason and because it is less susceptible to electrolytic action should, when possible, be used in preference to the latter. The resistance of a pipe line

can become very great with time, due to rust formation at the joints, which acts as a sort of self-protection. This effect may be increased by inserting insulating pieces at the joints.* This process not only diminishes the leakage currents by increasing the soil resistance ($r_e$), but also that portion of leakage current which enters the pipes. Such insulation joints also prevent the carrying of higher potentials from a distance to points near the tracks. The V. D. E. code recommends the insertion of insulating joints as an important means of protecting pipes.†

By insulating the rails and the pipes, both the current leakage from the rails and the entrance of current into the pipes is rendered more difficult.

Railways with their own special roadbed can generally be so well insulated that no fears as to the leakage of current need be entertained.

To such roads, where a well-drained and, therefore, a poor conducting or perhaps a truly insulating roadbed (as wooden ties on gravel or asphalt, etc.) is used and leakage of current is very slight, the V. D. E. code does not apply.

In interurban roads of considerable length where the earth is not used as return, considerable drop of potential may occur in the track. At road crossings the resistance of the leakage path is greatly reduced. Therefore, in certain cases, the existence of potential differences between the surrounding earth and the tracks sufficiently great to endanger animals is possible. This evil can be avoided

* Kinckling observed a 6 inch cast iron gas main in Syracuse, N. Y., with cement joints having a resistance of 12,000 ohms per 100 feet, which was not free from electrolysis. *Municipal Jour. and Engr.*, Vol. XV, p. 97 (1903).

† Brown, from experience in Dayton, O., recommends the replacement of old pipes with wooden pipes bonded and covered with asphaltum, also that such wooden pipes be inserted in the lines which lie in the danger zones. *Municipal Engineering,* Vol. XVI, p. 84 (1899).

by grounding the rails at the crossings, but then the grounding would cause the leakage of current, the very thing which the track was insulated to prevent. The section at the crossing can be disconnected from the rest of the track, but it is not often practicable to do this.

In such cases, Kallmann recommends a "partial ground," which is obtained by connecting a coil of bare copper wire to the track and burying it about one half or one meter in the ground. Such an arrangement does not permit the development of large stray currents and yet it distributes the potential in such a manner that no harm can come to animals in crossing the tracks.

In railways which do not have their own special roadbed it is impossible to completely insulate the track. However, the insulation should be made as good as possible, there being little to fear from potentials that would endanger the life of man or beast.

The pipes cannot always be perfectly insulated * because of the great cost. According to V. Gaisberg † pipes tarred in the ordinary way ‡ have stood the electrolytic action better than those protected by a covering of pitch, although the latter will last longer under ordinary circumstances. In general it may be said that coverings which protect the pipes from rust will also protect them from corrosion.§ The composition of the insulator and the method of applying are very important.

* Schieman says the insulation of pipes is out of the question. Bau ü Betrieb elektrischer Bahnen (1900).

† *E. T. Z.*, 1903, p. 492.

‡ Knickling states that coal tar coating is not adequate protection, *Municipal Jour. and Engr.*, Vol. XV, p. 97 (1903).

§ McGowan cites cases in Brooklyn, where 2 inch pipes which formerly lasted but nine months were covered with an insulating compound of coal tar and rubber, and at the date of writing had been down two years and no trouble yet. *Stevens Institute Indicator*, Vol. XVIII, p. 163 (1901).

The insulator must not contain any injurious substances, such as ammonia or acids, and must be applied while hot to a perfectly clean surface. Janke * recommends the application of two such coats. Before the insulation paint has become hard, the pipe should be wound with jute strips about 200 millimeters (8 inches) wide and then two coats of tar applied on top of the jute. The completed covering is about 5 millimeters thick.

The resistance of the path from the track to the pipes decreases as pipes approach the tracks. Therefore, in order that a high current density may not occur in the pipes, they should not be brought too near the tracks. This is especially true of places near the feeding points, because high current densities at such points are accompanied by strong electrolytic action.

According to the V. D. E. code, the feeding points should be located as far from pipes as possible, and especially from crossing points and branch pipes. If it is impossible to do this, that portion of the pipe which is near the tracks must be insulated from the rest of the system by inserting insulating joints, and should this not be possible a layer of insulation between the pipes and tracks must be used.

The pipes are damaged at the points where the currents leave them. And for this reason it is advisable to ground the pipes at such points. If the ground is properly made, most of the current will leave through the ground plate and the electrolytic action will be transferred from the pipe to the plate.* Old worn-out pipes may be used as ground plates. This grounding protects the pipes only when they have good electrical joints. The pipe currents are in-

* Verhandlungen des Vereins zur Förderung des Gewerbefleisses, Bericht vom 4 Jan., 1904.

* Hering suggests connecting blocks of zinc to the pipes in the danger zones, maintaining that the zinc will act electro-chemically to induce the current to leave through the zinc. Trans. Amer. Electrochemical Soc., Vol. III, p. 195 (1903).

creased, and when the pipes are electrically connected the total leakage currents are increased, and other metallic masses which are not grounded are thus subjected to a greater danger risk. According to experiments made in Boston,* the distribution of potential in the earth is but slightly altered by grounding.

When a high potential exists between an ungrounded pipe and the earth, the pipe is subjected to a great danger risk; should this potential be reduced to zero by grounding, the distribution of potential will be changed and in certain cases other pipes in the vicinity may become damaged. Thus it is seen that the grounding of pipes can be resorted to only in special cases.

The same purpose, namely, that of leading currents out of the pipes without doing damage, is attained by connecting the pipes to the rails at the feeding points or to the negative bus bar at the station.† This arrangement has a much greater effect ‡ than grounding, since by direct connection the resistance between the pipe and track may be made as small as desired. The protection extends only so far as the pipes are electrically connected.

The leakage currents by the reduction of the resistance of the leakage path will be enormously increased, and pipes in the vicinity which are not protected may be greatly damaged. Therefore, all pipes located in the danger district must be protected by connecting them to the rails.

* Bell, Power Distribution for Electric Railways, p. 43.

† McGowan cites cases in Brooklyn where pipes which formerly lasted but six months, had been bonded to the power house and up to the date of writing, which was five years later, they had given but little trouble. *Stevens Institute Indicator*, Vol. XVIII, p. 163 (1901).

Adams states that pipes should not be bonded to any part of the railway system, but that continuous cables may advantageously be bonded to rails or power house in danger districts. *Municipal Engineering*, Vol. XVIII, p. 1 (1900).

‡ Krohn, *E.T.Z.*, 1901, p. 269.

Since this is seldom possible, the connection of rails and pipes is not to be recommended. According to the V. D. E. code, the pipes must not be connected to the rails.

The same is true of the use of negative boosters * connected to the pipes. If a dynamo or battery is connected between the pipes and the rails or negative feeders (Fig. 28), the pipes will take on a potential lower than the surrounding earth or the tracks, and no currents will leave the pipes. The pipes are thus protected as long as they are electrically connected. However, all unprotected pipes and

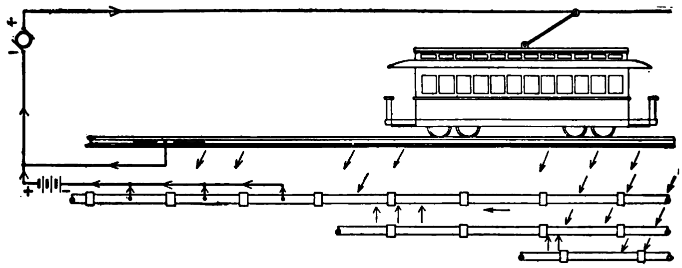

FIG. 28.

metallic structures will become greatly endangered because of the enormous increase in stray currents. The greater the E.M.F. of the battery or booster, the greater the leakage, and therefore the greater the current density in the earth. Even though the booster be so wound as to adjust itself to the load, this method can only be used in exceptional cases.

It has been suggested that the stray currents could be collected before they enter the pipes by laying a bare wire near the rails. Such an arrangement decreases the soil resistance and increases the leakage currents, and a large portion of these currents, in spite of the protecting wire,

* Teichmüller, *E.T.Z.*, 1900, p. 436.

succeed in entering the pipes. Therefore, this measure has but little effect. The pipes can also be protected by laying them within another pipe.

According to Petri,* the pipes to be protected should be partially or completely surrounded by a protecting pipe or plate and electrically connected to it. That which was said concerning grounding is partially applicable here. The corrosion takes place in the protecting pipes. This method of protection can be used only in special cases where pipes are in great danger and there is no other way of protecting them.

If the current decreases uniformly as we recede from the feeding point, from formulas (13) and (14) the potential at the feeding point is double that at the middle point (half way between the feeding points). Therefore, the potential of the pipes with reference to the earth is greatest near the feeding points, and the current density greatest at the very point where there is the most danger. This leads to the suggestion that the rails be connected to the positive pole of the machine, which would reduce the current density at the danger point to about one half. However, the pipes would be damaged throughout a greater length. The strength of the leakage current (formula 16) and that of the corrosion current (formula 18), is independent of the direction of the power current. The corrosion currents, and therefore the corrosion, is not reduced by reversing the direction of the power current. If there are places near the feeding points where the pipes are badly corroded and where there is a high current density, the trouble can be remedied by reversing the polarity of the system, although the total corrosion currents will not be reduced. Thus it is seen that the polarity of the system has little effect upon the electrolytic action in the pipes.

The method of connecting the tracks to the negative has

* D. R. P., No. 126,496.

come into general use because positive conductors are more easily insulated.

Although little is to be gained by a simple reversal of the polarity, a periodical reversal of the polarity may prove very advantageous.

According to experiments by Larsen,* daily reversals of polarity reduce the electrolytic action to one fourth, and hourly reversals to one thirtieth of its normal value. The changing of the direction of the current causes a partial restoration of the metal which has been removed, this effect increasing with the frequency of the reversals. Also, according to Larsen, the nature of the electrolytic action is less harmful when the polarity is periodically reversed than when it remains always the same. When the current flows continuously in the same direction, the pipes become deeply pitted, but when the polarity is periodically reversed the corrosion is more widely and uniformly distributed. Therefore, in all cases where the conditions permit, it is advisable to reverse the polarity of the system at certain intervals.

The hourly reversal of polarity reduces corrosion to a very great extent, but when alternating current, even of low frequency, is used the corrosion is completely done away with.†

The apparent resistance of the rails is greater for alternating current than for direct, and the higher the frequency the greater this difference. Thus, other things remaining the same, the leakage currents are greater when a road is operated with alternating current than when with direct, but this matters little since such currents do not cause corrosion.

In order to avoid heavy currents in the rails, roads have been constructed like the three-wire systems, the rails being

* *E. T. Z.*, 1902, p. 868.

† S. M. Kinter shows this experimentally in *The Electric Journal*, Vol. II., p. 668.

the neutral. In single-track roads the trolley wire is divided into sections * insulated from each other and successively connected to opposite poles of the generator. In double-track roads the trolley wires are the outside wires and the rails the neutral wire of the three-wire system. The tracks must be cross bonded at short intervals, in order to insure an even current distribution. This method of unloading the rails is very effective when there is an equal number of cars on each track and they are spaced at approximately equal distances from the feeding points so that the currents can be neutralized in the shortest possible length of track. Even though the rails may carry heavy currents for short distances, the potential drop cannot be great and thus the leakage currents will be reduced. The direction of the current in the rails depends upon the location of the cars, so that it is continually changing.

This continual reversing of the current contributes a great deal to the reduction of the electrolytic action in the pipes. The potential of the trolley with reference to earth is not increased in the three-wire system, but the potential between the two trolley wires is doubled, and therefore the insulation made more difficult.

The leakage currents are proportional to the square of the length of the section (half the distance between feeding points). The reduction of this length is therefore very effective. It is reduced by shortening the distance between feeding points. In order to make the feeders effective for each point, it does not suffice to simply connect the various points to the power station through copper conductors; but the different feeders must be so chosen that the drop in potential from the feeding point to the power house is the same in all cases. This result is obtained by inserting resistance in the feeders for the points near the power house (Fig. 29). When the resistances are properly chosen

* Schiemann, Bau ŭ Betrieb elektrischer Bahnen, 1900, p. 268.

and the potential drops properly equalized there will be little or no potential difference between the different feeding points. If the feeder cables carry pilot wires the latter may be used for finding the potential difference between feeding points. The feeding of the trolley wire is entirely independent of the number or location of the negative

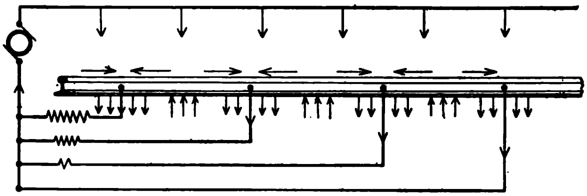

FIG. 29.

feeders. This method of arranging negative feeders has shown itself to be very effective and because of its great simplicity has found a wide application.

The only disadvantages of this arrangement are that a great deal of energy is wasted in the resistances, and that

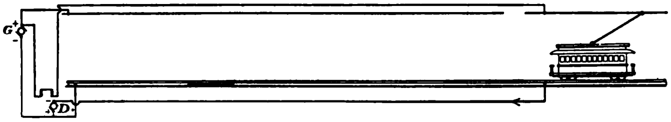


FIG. 30.

with continually changing loads in the different feeder sections the feeding is not automatically regulated.

These disadvantages are avoided in Kapp's arrangement of the negative feeders,* such as shown in Fig. 30. *G* is the generator in the power house, *D* the negative booster,

* D. R. P. No. 88,275. *E. T. Z.*, 1896, p. 43. Rasch, *E. T. Z.*, 1896, p. 34. Teichmüller, *E. T. Z.*, 1900, p. 436. Krohn, *E. T. Z.*, 1901, p. 269.

which is driven by an electric motor. The field of the booster is excited by the line current.

By means of resistances, not shown in Fig. 30, the speed of the motor is regulated and the E.M.F. of the booster varied through a wide range. In Bristol with the above arrangement the loss of potential was reduced from about 10 volts to about 2½ volts. If once properly adjusted for any given load the apparatus regulates automatically for any other load, since the field excitation is proportional

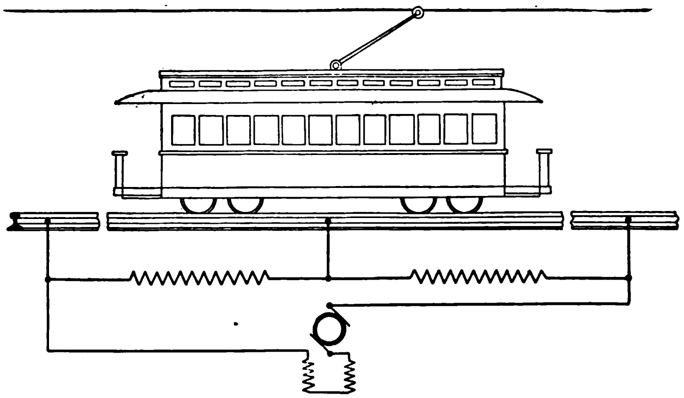

FIG. 31.

to the load, granted, of course, that the machine is worked below saturation. When a negative booster is used in a larger system which has several trolley feeders, the field winding is so connected that the total current of the various feeders passes through it. If each negative feeder is connected to a booster of its own, it is possible to so regulate the machines as to reduce the potential difference between feeding points to any desired value. In Glasgow there are over a dozen Kapp negative boosters * installed in the various sub-stations, one for every 1,000 amperes, by means

* *E. T. Z.*, 1902, p. 19.

of which the potential difference between feeding points is kept below one volt.

In certain cases, for instance, where there is a long track without branches, such as an interurban railway, it is not necessary to keep the rail potential as low as in street railways. Gisbert Kapp has also a method * of avoiding high potentials in such cases. The arrangement is shown in Fig. 31. A short section of track is disconnected and insulated from the rest, and the parts on each side of the section connected through a series dynamo. This dynamo, which

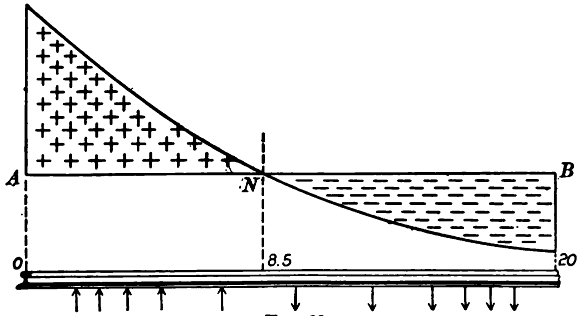


FIG. 32

is motor driven, generates an E.M.F. which equalizes the loss in the rails. In order that the insulated section shall not be dead, it is connected to the rest of the track through resistance, so that a car stopping on the section can start again. This arrangement can be placed at certain intervals along the track. The boosters can be set in little houses along the track and do not need constant attendance.

The boosters should be placed at shorter intervals near the feeding points than near middle points. In Fig. 32 the potential of the earth *AB*, with reference to the track, is shown. *A* is the feeding point, *B* the middle point, and,

* *E. T. Z.*, 1902, p. 19, D. R. P., No. 125, 762. Ziehl, *E. T. Z.*, 1902, p. 145.

$AB$ = 20 kilometers. Near $A$ the earth is positive (danger zone) to the track, and near $B$ negative. The shaded area above $AN$ represents the danger risk of continuous, electrically connected pipes. By putting Kapp negative boos-

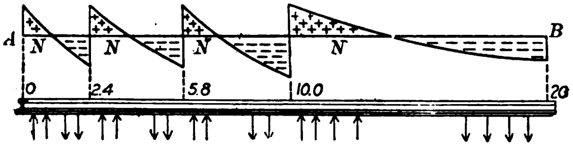


FIG. 33.

ters in at 2.4, 5.8, and 10 kilometers from the feeding point $A$, the potentials will be changed as seen in Fig. 33. Instead of one large danger zone, there will be four small ones with correspondingly lower potentials. Thus the leakage current will be decreased and the danger of corrosion reduced.

## CHAPTER XI

### OTHER DISTURBANCES CAUSED BY STRAY CURRENTS

IN that which has gone before only the corrosion effects of stray currents were spoken of, because in comparison with these the other disturbances are of minor importance. Then again, the pipe currents need to be looked after because they do not make their presence known until a long time has elapsed and considerable damage has been done, while the disturbances in physical instruments,* telephones, telegraphs, and signal apparatus, due to stray currents, show themselves immediately and in a most disagreeable manner.

The stray currents produce magnetic fields which change the components of the earth's field. The earth currents can distribute themselves over a great area, and therefore create disturbances at considerable distances. When strong earth currents are purposely generated, it is possible to detect them at distances of several kilometers from the generating point.† Stray currents from an electric railway were detected at a distance of 3 kilometers by Strecker.‡ By setting up intermittent earth currents of from 14 to 19 amperes along a stretch of 3 kilometers, the same experimenter, succeeded in detecting branch currents at a distance of 17 kilometers. The magnetic disturbances do not cease immediately after the railway has been shut down. The magnet needle returns gradually to its former position §

* *E. T. Z.*, 1895, pp. 417 and 443.

† Rathenan, Telegraphic ohne metallische Leitung, *E. T. Z.*, 1894, p. 616.

‡ *E. T. Z.*, 1896, p. 106. § Strecker, *E. T. Z.*, 1895, p. 424.

after the railway has been put into operation, this lag is undoubtedly due to the gradual demagnetization of the magnetized iron parts and also to polarization currents.

At the request of V. Bezold,* Edler,† in Spandau, made measurements up to distances of 7.48 kilometers, with the highly sensitive apparatus of Eschenhagen, in order to determine the influence of leakage currents from railways upon magnetometric measurements. The disturbance of the horizontal force was found to be nearly inversely proportional to the distance from the tracks, but that of the vertical component decreased much more rapidly with the increase of distance from the tracks. The disturbances within the district where the observations were made were such that the most accurate magnetometric measurements could not be carried on. As a result of these experiments V. Bezold states that no electric railway with rail return should be allowed within 15 kilometers (9.38 miles) of an observatory where fundamental magnetic observations are continually carried on.

Roads with double trolley cause but little trouble, the disturbances not being perceptible for more than a kilometer.

President Kohlrausch, of the Reichsanstalt, in Berlin, requires that the disturbances in that institution shall not amount to more than $\frac{1}{10}$ of a minute-arc.

For physical laboratories, where fundamental magnetic observations are not continually carried on, and where protected instruments are used, these distance limits can be greatly reduced.

This is particularly the case when protected instruments are used. Galvanometers of the D'Arsonval type with stationary permanent magnets do not use the earth's field, and are therefore not sensitive to disturbances of the same, and can be used in the immediate neighborhood of an elec-

* *E. T. Z.*, 1900, p. 160. † *E. T. Z.*, 1900, p. 193.

tric railway, as, for instance, in testing the insulation of cables. Galvanometers which use the earth's field can be protected from the disturbances of stray currents. In the iron-clad galvanometers of Du Bois and Rubens * the needle is protected by an iron armor which acts as a screen for magnetic lines. An unshielded astatic galvanometer can be protected by laying a bundle of iron near the upper magnets.

When considerable potentials exist between the ground plates at the different stations, troubles can arise in telephone, telegraph, and signal systems, with ground return, due to stray currents entering their circuits. If the ground plates at the different stations are so laid that no potential differences occur between the different plates (Fig. 9), the disturbances will cease. In many cases this is not possible, and it only remains to use a metallic return.

It is well known that a telephone is a highly sensitive detector of alternating current. Therefore, the entrance of the smallest amount of stray current into the telephone circuit makes itself disagreeably noticeable.

The high frequency pulsations and not the variations of the current due to change in load are the cause of the disturbance in the telephone. These pulsations are caused by coils being short circuited by the brushes on the generators and motors, by varying reluctance of the revolving slotted armature, by vibration of the brushes, by sparking, etc. The working current is, therefore, not a perfectly continuous current. It can be divided into a purely continuous current and a superposed alternating current. Only the latter causes telephone disturbances.

The strength of the pulsations, and therefore the loudness of the noise in the telephone receiver, depends upon the construction of the generators and motors. Self-induction weakens and capacity strengthens the pulsations. Series

* Zeitschrift für Instrumentenkunde, 1900, p. 65.

motors because of the choking action of the field coil give rise to less trouble from pulsations than shunt motors. The presence of such pulsations may be detected by inserting a current transformer in the motor or generator leads and connecting a telephone receiver across the secondary (Fig. 34).

The current transformer can be easily constructed by winding a bundle of iron sheets or wires with a considerable number of turns of fine wire and a small number of turns of heavy wire.

Where floating batteries are used in the power station, most of the pulsations caused by the generator will be

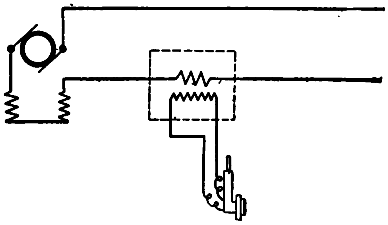

Fig. 34.

absorbed by them. The floating battery tries also to absorb the pulsations caused by motors on the line, and in this way strengthens the pulsations set up by the motors. The same is true of storage battery cars, which charge from the trolley while under way. The battery on the car absorbs the pulsations caused by the motors on that car, but strengthens any pulsations generated outside of the car. If each car has a battery connected in parallel with the motors all pulsations generated in the motors will be absorbed and kept off of the line. In such cases the only pulsation currents on the line come from bad contact at the wheels or trolley, which cause equalization currents to flow from the batteries. Such pulsations can, in certain

cases, become more disagreeable in telephone systems than the ones caused by the motors themselves.

The greater share of the disturbances which are caused by current pulsations do not come from currents entering the telephone circuit, but from the induction and condenser effects of the power circuit upon the telephone circuit. Since, however, the rail opposes the flow of alternating current more than that of direct, it is probable that the earth currents contain a larger per cent of alternating current than of direct, so that in exceptional cases the effects of the earth currents entering the circuits may be greater than that of induction.

If the telephone circuits are disturbed by railway currents, the starting, running, and stopping of the cars is clearly heard in the telephone receiver. If such disturbances are caused by currents entering through the ground plates, they may be removed by properly setting the ground plates. The entrance of earth currents can be decreased or entirely avoided if the local conditions permit the setting of the ground plates in neutral districts or in such a manner that no potential exists between the different plates. This method is, however, not very reliable, because of the continuously fluctuating and shifting load currents. A better method is to reduce the pulsations by the use of suitable choke coils. These choke coils may be constructed in the same manner as the transformer, by winding a laminated core with a suitable number of turns of wire. It is not sufficient to place a choke coil in the power house, because a portion of the pulsations are transmitted only between the motors and do not enter the power house at all. Therefore, it is wiser to equip each car with a choke coil or else to insert them in the overhead circuit at certain intervals all along the track. A disadvantage of the choke coil is its continual consumption of energy. If liquid condensers, for instance, aluminum condensers, are connected

in parallel with the car motors, smaller choke coils may be used.

In alternating current railways, using current of low frequency, no trouble is experienced in telephone circuits, when the current wave is a pure sine wave and contains no higher harmonics.

Since the harmonics are always present, the low frequency alternating currents disturb telephone circuits when the rails are used as return conductors.

# CHAPTER XII

## CONCLUSIONS

If the rails used to carry return currents are not fully insulated from the earth, it is impossible to entirely prevent the leakage of current. Also, if the pipes are not perfectly insulated from the earth, stray currents cannot be prevented from entering them. Earth currents can only be entirely prevented when both positive and negative conductor are insulated, as may be done in conduits in cities and with two trolleys outside. If it is impossible to thoroughly insulate the circuit, in cities where there are extensive systems of pipes precautions can be taken so as to reduce the earth currents to such an extent as to render them harmless.

The prophecies that were made by different ones at the beginning, saying that the usage of the rails as return conductor would, through electrolytic action, cause great damage to gas and water pipes, have not been fulfilled. In 1899 the Elektrotechnischer Verein in co-operation with the Verein Deutscher Strassen und Kleinbahnverwaltungen, made inquiries of electric railway, gas, and water * companies in ninety German cities where electric railways are operated, and found that in only two or three cases had there been any trouble from the leakage currents.

These cases of corrosion occurred in places where the current density was very great. It was possible to remove the danger † in each of these cases by taking certain pre-

* West, *E. T. Z.*, 1900, p. 706.

† V. Gaisberg, Rohrzerstörung beim Ausbau des Hamburger Netzes ŭ dagegen getroffene Massnahmen, *E. T. Z.*, 1903, p. 492.

cautions. What precautions are to be taken must be determined from a consideration of the local conditions so as to best satisfy the interests of all concerned.

Both the railway company and the companies operating the pipe lines must co-operate in determining the preventative measures to be employed, since each can do a great deal to reduce or remove the danger of corrosion.

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